U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-257 133

Monitoring Groundwater Quality: Methods and Costs

General Electric Co.

Prepared for

Environmental Monitoring and Support Lab, Las Vegas, Nev

May 76

BEST SELLERS

FROM NATIONAL TECHNICAL INFORMATION SERVICE

NTIS

Solar Heating and Cooling in Buildings: Methods of Economic Evaluation
COM–75–11070/PAT 48 p PC$4.00/MF$2.25

Design and Construction of a Residential Solar Heating and Cooling System
PB–237 042/PAT 233 p PC$8.00/MF$2.25

Performance of a Residential Solar Heating and Cooling System
PB–244 644/PAT 62 p PC$4.50/MF$2.25

Solar Energy
AD–778 846/PAT 478 p PC$12.50/MF$2.25

Stimulation of Geothermal Energy Resources
ERDA–37/PAT 52 p PC$4.50/MF$2.25

An Assessment of Industrial Energy Options Based on Coal and Nuclear Systems
ORNL–4995/PAT 329 p PC$10.00/MF$2.25

Environmental Impact Statements: A Handbook for Writers and Reviewers
PB–226 276/PAT 207 p PC$7.75/MF$2.25

Environmental Protection Guidelines for Construction Contract Specification Writers
ADA–014146/PAT 124 p PC$5.50/MF$2.25

A Review and Analysis of Environmental Impact Assessment Methodologies
ADA–013 359/PAT 21 p PC$3.50/MF$2.25

Procedures for Reviewing Environmental Impact Assessments and Statements for Construction Projects
ADA–015 020/PAT 25 p PC$3.50/MF$2.25

Computers in the 1980's: Trends in Hardware Technology
AD–783 323/PAT 20 p PC$3.50/MF$2.25

Minicomputers: A Review of Current Technology, Systems, and Applications
AD–783 316/PAT 104 p PC$5.50/MF$2.25

Microprocessor/Microcomputer Software Systems: Present and Future
ADA–013 322/PAT 25 p PC$3.50/MF$2.25

An Air Force Guide to Contracting for Software Acquisition
ADA–020 444/PAT 45 p PC$4.00/MF$2.25

A Dictionary for Unit Conversion
PB–249 659/PAT 456 p PC$17.50/MF Not Available

HOW TO ORDER

When you indicate the method of payment, please note if a purchase order is not accompanied by payment, you will be billed an addition $5.00 *ship and bill* charge. And please include the card expiration date when using American Express.

Normal delivery time takes three to five weeks. It is vital that you order by number or your order will be manually filled, insuring a delay. You can opt for *airmail delivery* for a $2.00 charge per item. Just check the *Airmail Service* box. If you're really pressed for time, call the NTIS Rush Order Service. (703) 557-4700. For a $10.00 charge per item, your order will be airmailed within 48 hours. Or, you can pick up your order in the Washington Information Center & Bookstore or at our Springfield Operations Center within 24 hours for a $6.00 per item charge.

You may also place your order by telephone or TELEX. The order desk number is (703) 557-4650 and the TELEX number is 89-9405.

Whenever a foreign sales price is NOT specified in the listings, all foreign buyers must add the following charges to each order: $2.50 for each paper copy; $1.50 for each microfiche; and $10.00 for each Published Search.

Thank you for your interest in NTIS. We appreciate your order.

METHOD OF PAYMENT

☐ Charge my NTIS deposit account no.__________
☐ Purchase order no.__________
☐ Check enclosed for $__________
☐ Charge to my American Express Card account number

☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐

Card expiration date__________
Signature__________
☐ Airmail Services requested

NAME__________
ADDRESS__________
CITY, STATE, ZIP__________

Item Number	Quantity		Unit Price*	Total Price*
	Paper Copy (PC)	Microfiche (MF)		

*All Prices Subject to Change
10/76

Sub Total __________
Additional Charge __________
Enter Grand Total __________

Clip and mail to:

NTIS
National Technical Information Service
U.S. DEPARTMENT OF COMMERCE
Springfield, Va. 22161
(703) 557-4650 TELEX 89-9405

253015

PB 257 133

EPA-600/4-76-023
May 1976

Environmental Monitoring Series

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into five series. These five broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The five series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies

This report has been assigned to the ENVIRONMENTAL MONITORING series. This series describes research conducted to develop new or improved methods and instrumentation for the identification and quantification of environmental pollutants at the lowest conceivably significant concentrations. It also includes studies to determine the ambient concentrations of pollutants in the environment and/or the variance of pollutants as a function of time or meteorological factors.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

PB257133

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/4-76-023

2.

3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE
MONITORING GROUNDWATER QUALITY: METHODS AND COSTS

5. REPORT DATE
May 1976

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
L. G. Everett, K. D. Schmidt, R. M. Tinlin, and D. K. Todd

8. PERFORMING ORGANIZATION REPORT NO.
GE75TMP-69

9. PERFORMING ORGANIZATION NAME AND ADDRESS
General Electric Company-TEMPO
Center for Advanced Studies
P. O. Drawer QQ
Santa Barbara, California 93102

10. PROGRAM ELEMENT NO.
1HA326

11. CONTRACT/GRANT NO.
69-01-0759

12. SPONSORING AGENCY NAME AND ADDRESS
Environmental Monitoring & Support Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Las Vegas, Nevada 89114

13. TYPE OF REPORT AND PERIOD COVERED
Final

14. SPONSORING AGENCY CODE
EPA-ORD Office of Monitoring and Technical Support

15. SUPPLEMENTARY NOTES
This is one of 5 final reports in a series of 11 documents prepared on monitoring groundwater quality.

16. ABSTRACT

This report describes various groundwater monitoring methods and provides a generalized cost breakdown of the major economic factors for each method. All possible groundwater-related measuring techniques applicable at the land surface, topsoil, vadose zone and zone of saturation are presented. Each monitoring method is described, referenced and illustrated. Estimates of itemized capital and operational costs are presented. The material is presented for in-depth reference purposes without recommendation for least-cost techniques, a least-cost mix of groundwater monitoring approaches, or an optimal information system.

PRICES SUBJECT TO CHANGE

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Cost analysis Ground water Monitors Water pollution Water quality Water resources Water wells	Aquifer characteristics Aquifers Water monitoring methods Groundwater monitoring costs	08H 13B 14A

18. DISTRIBUTION STATEMENT
RELEASE TO PUBLIC

ia

19. SECURITY CLASS *(This Report)*
UNCLASSIFIED

20. SECURITY CLASS *(This page)*
UNCLASSIFIED

21. NO. OF PAGES
152

22. PRICE
$6.75-2.25

EPA Form 2220-1 (9-73)

☆GPO 691-221-1976

EPA-600/4-76-023
May 1976

MONITORING GROUNDWATER QUALITY: METHODS AND COSTS

by

Lorne G. Everett
Kenneth D. Schmidt
Richard M. Tinlin
David K. Todd

General Electric Company—TEMPO
Center for Advanced Studies
Santa Barbara, California 93101

Contract No. 68-01-0759

Project Officer

George B. Morgan
Monitoring Systems Research and Development Division
Environmental Monitoring and Support Laboratory
Las Vegas, Nevada 89114

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF RESEARCH AND DEVELOPMENT
ENVIRONMENTAL MONITORING AND SUPPORT LABORATORY
LAS VEGAS, NEVADA 89114

i b

This report has been reviewed by the Environmental Monitoring and Support Laboratory—Las Vegas, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ACKNOWLEDGMENTS

Dr. Richard M. Tinlin, Dr. Lorne G. Everett, and the late Dr. Stephen Enke of General Electric—TEMPO were responsible for management and technical guidance of the project under which this report was prepared.

Dr. Everett and Dr. Kenneth D. Schmidt, a consultant to TEMPO from Fresno, California, were principal authors of the report. Dr. L. Graham Wilson, a consultant to TEMPO from Tucson, Arizona, made contributions to the technical content. Dr. David K. Todd, a consultant to TEMPO from Berkeley, California, also provided technical guidance and review.

The following officials were responsible for administration and technical guidance of the project for the U.S. Environmental Protection Agency:

Office of Research and Development (Program Area Management)

Mr. Albert C. Trakowski, Jr.
Mr. John D. Koutsandreas

Environmental Monitoring and Support Laboratory Las Vegas
(Program Element Direction)

Mr. George B. Morgan
Mr. Edward A. Schuck
Mr. Leslie G. McMillion
Mr. Donald B. Gilmore

ABSTRACT

This report describes various groundwater monitoring methods and provides a generalized cost breakdown of the major economic factors for each method. All possible groundwater-related measuring techniques applicable at the land surface, topsoil, vadose zone and zone or saturation are presented. Each monitoring method is described referenced and illustrated. Estimates of itemized capital and operational costs are presented. The material is presented for in-depth reference purposes without recommendations for least-cost techniques, a least-cost mix of groundwater monitoring approaches, or an optimal information system.

TABLE OF CONTENTS

Page

ACKNOWLEDGMENTS iii
ABSTRACT iv
LIST OF ILLUSTRATIONS vi
LIST OF TABLES viii

SECTION I — INTRODUCTION 1
  Purpose 1
  Scope 1
  Hydrogeological Framework 2
  Groundwater Monitoring Methods 4
  Types of Cost 5

SECTION II — MONITORING AT THE LAND SURFACE 11
  Introduction 11
  Nonsampling Methods 11
  Sampling Methods 25

SECTION III — MONITORING IN THE VADOSE ZONE 29
  Introduction 29
  Soil Sampling and Well Drilling 31
  Determination of Water Content 33
  Determination of Water Movement 42
  Water Movement in the Unsaturated State 44
  Water Sampling in the Vadose Zone 49

SECTION IV — MONITORING IN THE ZONE OF SATURATION 57
  Introduction 57
  General Monitoring Procedures 57
  Specific Monitoring Methods 62

SECTION V — ANALYSIS OF SAMPLES 100
  Introduction 100
  Custody Control 100
  Quality Control 103
  Soil 105
  Water 113

REFERENCES 130

APPENDIX — METRIC CONVERSION TABLE 140

LIST OF ILLUSTRATIONS

Figure No.	Title	Page
1	Schematic diagram of groundwater pollution from surface sources.	3
2	Small-diameter well costs index and the ENR materials component.	6
3	Large-capacity well costs index and the ENR construction cost index.	7
4	Cost of testing submerged tanks of various volumes, November 1974.	14
5	Alerting procedure chart for hazardous material spills.	24
6	Cost of power-augering 8-inch diameter sample holes to various depths and hole densities, November 1974.	32
7	Sketch of neutron moisture logger and accessories.	34
8	Moisture logs showing growth and dissipation of mounds in the vadose zone.	37
9	Cost of neutron moisture logging for various depths and sample space densities, December 1974.	38
10	A single manometer tensiometer.	38
11	Cost of tensiometers for various depths and sample space densities, December 1974.	39
12	Cost of multiple electrical resistance blocks and soil moisture meter for various depths and sampling densities, December 1974.	40
13	Relationship between grain size and water-storage properties of alluvium from large valleys.	41
14	Cost of piezometers for various depths and sampling densities, November 1974.	44
15	Cross section of suction cup assembly and backfilling material.	53
16	Cross section of porous cup assembly with pressure control.	54

ILLUSTRATIONS (continued)

Figure No.	Title	Page
17	Cost of soil salinity sensors and a salinity bridge for various depths and sampling densities, November 1974.	56
18	Cost of shallow, small-diameter monitor wells, October 1974.	66
19	Updated (1975) cost of 4-, 5-, and 6-inch wells in sand and gravel.	77
20	Updated (1975) cost of 4-, 5-, and 6-inch wells in consolidated rock.	78
21	Generalized cost of coring in unconsolidated and consolidated formations, October 1974.	81
22	Cost of electrical conductivity (EC) and gamma logging, September 1974.	83
23	Cost of steel tapes, September 1974.	84
24	Cost of electric sounder and cable, September 1974.	85
25	Approximate cost of sampling wells (one round), December 1974.	90
26	Cost of cable and flex hose for use with portable submersible pumps, October 1974.	92
27	Power costs for continuous pumping of 1 hour, 1 day, 1 week, for specific pumping heads and specific discharge rates, December 1974.	97
28	Costs for determinations of water content and bulk density in soils, September 1974.	105
29	Modified Haines Apparatus for obtaining soil-water characteristic curves.	108
30	Soil-water characteristic curve, showing hysteresis.	109

LIST OF TABLES

Table No.	Title	Page
1	Example of ENR indexes for September 12, 1974	8
2	Example of EROS data center standard costs—satellite products, October 1974	17
3	Land-use classification system for use with remote-sensor data	20
4	Total cost of aerial surveillance for land-use mapping, July 1974	21
5	Specific yield values assumed for the southern part of the Central Valley, California	42
6	Earth resistivity survey costs, December 1974	64
7	Costs in dollars for well drilling in unconsolidated formations, EPA Regions III and IV, October 1974	70
8	Costs in dollars for well drilling in consolidated formations, EPA Regions III and IV, October 1974	71
9	Black pipe casing costs for wells in dollars, EPA Region IX, October 1974	72
10	PVC pipe costs for wells in dollars, EPA Region IX, October 1974	72
11	Average cost of submersible water pumps, found in EPA Region IX, October 1974	93
12	Hydrologic laboratory tests and cost schedule, September 1974	110
13	Recommended sampling and preservation techniques for inorganic chemical determinations	119
14	Costs of inorganic chemical determinations for groundwater pollution, October 1974	122
15	Costs of organic chemical determinations for groundwater pollution, October 1974	125
16	Recommended sampling and preservation techniques for organic chemical determinations	126

TABLES (continued)

Table No.	Title	Page
17	Costs of bacterial analysis for groundwater pollution, October 1974	128
18	Costs of radiochemical analysis in groundwater pollution, October 1974	129

SECTION I

INTRODUCTION

This report is one of a series of five reports on the general subject of monitoring groundwater quality. The basic report in the group is Monitoring Groundwater Quality: Monitoring Methodology (Todd et al., 1976), which outlines a procedure for creating a monitoring program for groundwater quality under the general supervision of the U.S. Environmental Protection Agency. As an essential supplemental reference to the methodology volume, this report documents the various methods and techniques available to monitor groundwater quality and also presents detailed cost data for the methods and techniques. Monitoring has been broadly interpreted to include all possible measuring techniques with the intent to make this report as useful as possible.

PURPOSE

Developing a groundwater monitoring program in an area requires not only an extensive understanding of the various monitoring techniques available but also a knowledge of their costs. Previous economic groundwater studies dealt primarily with the cost of supplying groundwater for municipal and industrial usage. More recent cost studies by D. J. Cederstrom (1970), James P. Gibb (1971), and Robert H. Forste (1973) are directed toward costs of producing wells of varying yields. In general, the subject of groundwater monitoring methods and their associated costs is fragmented throughout the hydrologic literature. The purpose of this report, therefore, is to provide a general summary of each of the groundwater monitoring methods such that a strategy can be derived based upon specific methods and actual cost data.

SCOPE

This report describes the various monitoring methods and provides a generalized cost breakdown of the major economic factors for each monitoring method. The itemization of factors for each method is not exhaustive, but it does serve to quantify reasonably well the cost of the monitoring technique. A cost interpretation structure to update the 1974 data presented herein and a scheme to cover the national spatial distribution of costs are provided. It should be emphasized that the costs listed are the best available estimates from sources that are believed to be reliable. Mention of specific products or services does not imply endorsement by EPA.

The material in this report is presented for reference purposes without recommendation for a least-cost technique, a least-cost mix of monitoring approaches, or an optimal information system. Essentially, the cost data are intended to serve as 'ine price guides for the various monitoring methods.* Furthermore, it should be noted that with few exceptions costs presented here are those associated with goods and services only. Any organized monitoring program in a local area will have personnel costs — supervisors, technicians, clerical staff, etc. — and overhead costs such as for offices, supplies, communication, and transportation. Thus, the data provide specific technical costs but do not attempt to encompass total budgets for monitoring programs.

HYDROGEOLOGICAL FRAMEWORK

The following discussion concerns the most common types of groundwater pollution from sources at or near the land surface. Seawater intrusion, deep well waste disposal, and groundwater overdraft are other types of water quality changes that are of major significance in many local areas. There are diffuse, line, and point sources of waste discharge. Figure 1 illustrates the sequence of events that occur when a well is polluted by surface wastes.

Considerable confusion exists in groundwater quality investigations because of a lack of understanding of the pertinent physical, chemical, biological, soil, and geologic factors. The diagram illustrates the five basic portions of the system: (1) the land surface, (2) topsoil, (3) vadose zone, (4) saturated zone, and (5) well. Sanitary engineers and surface water hydrologists focus attention primarily on water at the land surface. Soil scientists usually study the topsoil and secondarily the vadose zone. Geologists are generally concerned with the portion below the water table, while water supply agencies concentrate on well extraction where groundwater is used as a source of supply. The entire system illustrated in the simplified diagram must be studied in order to understand groundwater pollution.

Sampling at the land surface, in the topsoil, in the vadose zone, and from the saturated zone will be discussed in detail. Understanding of quality changes in the topsoil requires a knowledge of (1) soil water, (2) soil physics, (3) soil chemistry, (4) microbiology, and (5) physical chemistry. Historically, soil scientists have been concerned more with growing crops than with the quality of percolating waters. Today this situation has changed; now many studies concern the quality of percolate. An extensive body of literature is available on water quality changes in the topsoil, such as in Soil Science Society of America Proceedings and Journal of Environmental Quality. This information has often been overlooked in groundwater quality studies.

---

*Considerable assistance on cost data was provided by Federal and State agencies and several private companies.

Understanding of groundwater quality below the water table requires a knowledge of (1) hydrogeology, (2) well hydraulics, (3) geochemistry, and (4) physical chemistry. Of principal importance is knowledge of the hydrogeologic framework. The hydraulic and physical features of the groundwater system must be established before groundwater quality can be understood. An extensive body of literature is available on natural groundwater quality.

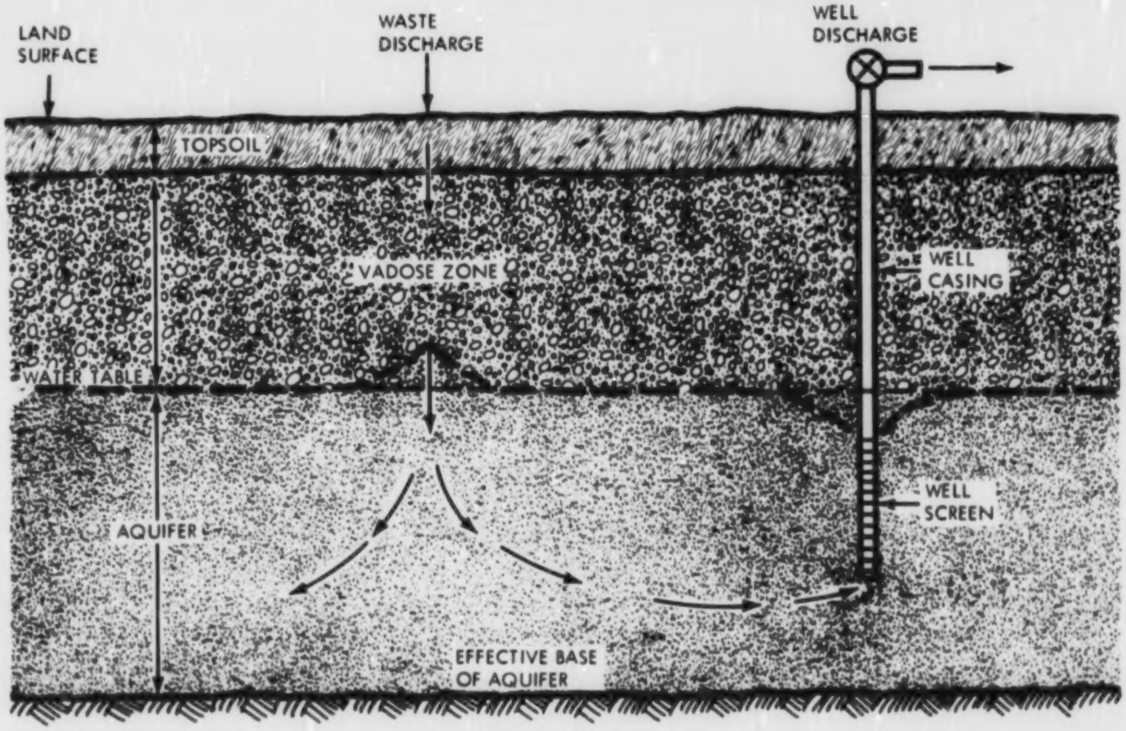

Figure 1. Schematic diagram of groundwater pollution from surface sources.

The vadose zone is commonly approached by the "black box" method, especially by geologists. Many vadose zones are not composed of "soil" in the sense of the topsoil known to agricultural workers. The vadose zone often extends to geologic formations beneath the topsoil. These may have different physical characteristics from the topsoil. Soil scientists have made great strides in analyzing the chemical quality changes that occur in the vadose zone (Wilson, 1971; Pratt, 1972; and Stout et al., 1965).

A major difficulty in past groundwater pollution studies has been the prediction of travel times of pollutants from the land surface to the water table. Predictions based on theoretical calculations often yield travel times that are much too slow. Two items argue for a relatively rapid vertical movement in many cases: (1) water balance calculations, i.e., comparison of leaching volumes versus storage capacity of the vadose zone; and (2) hydrologic and water quality evidence in areas where actual field measurements have been made (Wilson, 1971; and Stout et al., 1965). The rate of vertical movement of pollutants in the zone of aeration is of prime importance in developing a groundwater monitoring methodology.

GROUNDWATER MONITORING METHODS

The discussion of monitoring methods is presented in four sections: Section II, Monitoring at the Land Surface; Section III, Monitoring in the Topsoil and the Vadose Zone; Section IV, Monitoring in the Zone of Saturation; and Section V, Analysis of Samples. This order considers major subdivisions of a monitoring effort; however, it is not intended to convey the impression that the major subdivisions are not closely related. The successful implementation of a groundwater monitoring methodology will largely depend on an appropriate combination of monitoring methods.

Land surface monitoring includes sampling of surface water bodies for pollution, particularly streams and lakes, as well as rainfall sampling. Source monitoring deals with both solids and liquids that may impact on groundwater quality. Land surface monitoring thus includes water sampling, solids sampling, land use surveys, and inventories of amounts of wastes. The tools available besides sampling include remote sensing, pipeline and tank testing for leaks, and testing of artificial liners for leakage.

In most cases wastes applied at the land surface travel through significant thicknesses of topsoil and geologic materials before reaching the water table. Pollutants can be significantly retained or attenuated in the topsoil and the vadose zone. The storage capacity of the vadose zone for percolating waters may also be great. Long travel times from the land surface to the water table may necessitate detailed sampling in the vadose zone. Past studies in the vadose zone have largely been accomplished beneath point sources.

The primary site of groundwater quality monitoring lies in the saturated zone, as this is where water is ultimately pumped from wells for use at the land surface. Water sampling from wells is a key item, and along with source monitoring is the primary groundwater pollution monitoring approach. The techniques of well sampling and well drilling (for cases when existing wells do not suffice) are discussed extensively. Past groundwater pollution studies have demonstrated the usefulness of well sampling.

Subsurface sampling in both the vadose zone and in the zone of saturation requires considerable experience and careful judgement due to the complexity of most soil-aquifer systems.

TYPES OF COST

The cost structure is broken into four areas: capital, amortization, maintenance, and operational. The capital costs refer to those items that are fixed by location, such as screens, casings, pumps, or are fixed by their initial investment and subsequent repetitious use, such as pH meters, water samplers, etc. Interest on the initial capital investment may be considerable, especially over long periods of time. The annual writeoff or amortization expense of capital plus interest over each 1-year period is dependent upon the interest rate at which the money was loaned and the life of the depreciation fund or the effective life of the capital item. The effective life of water wells is about 20 years and the expected life of water pumps is about 10 years.

Based on the work of Cederstrom (1970), it is estimated that 1 percent of the total capital costs is sufficient to provide for the maintenance of drilled wells. Special consideration, however, is given to small-diameter driven wells as these are more frequently replaced in total. The operational costs of groundwater monitoring are a major item. Capital, amortization, and maintenance costs relate primarily to wells, while the remaining monitoring methods are primarily service functions involving operating costs.

Updating Cost Data

Rapid changes in the cost of labor and materials within the United States require that published cost data be updated to current costs prior to use. A convenient method to update costs is based upon the Engineering News-Record (ENR) indexes. Verification of cost estimates can be made by obtaining bids on specific items.

The Engineering News-Record Construction Cost Index was created in 1921 to diagnose the erratic price gyrations that occurred during and immediately following World War I and to evaluate their effects on construction costs. The index was designed as a general purpose construction cost index to chart basic costs. It is a weighted aggregate index of constant quantities of structural steel, portland cement, lumber, and common labor. This hypothetical block of construction, repriced weekly, was valued at $100 in 1913 prices. The original use of common labor in the Construction Cost Index was based on the idea that it set the trend for all wage rates. In the 1930's, however, wages plus fringe benefits climbed faster for laborers than for the skilled trades.

The Engineering News-Record Building Cost Index was introduced in 1938 to weigh the impact of skilled labor on cost trends. For its labor component it uses an average of carpenter, bricklayer, and structural ironworker wages. Its materials component is the same as used in the Construction Cost Index.

Figure 2 shows the time variation of well construction costs and the materials component of the ENR index. It can be seen that domestic and farm well costs agree closely with the trend of the index. Similarly, Figure 3 shows that large-capacity well costs are associated with the Construction Cost Index.

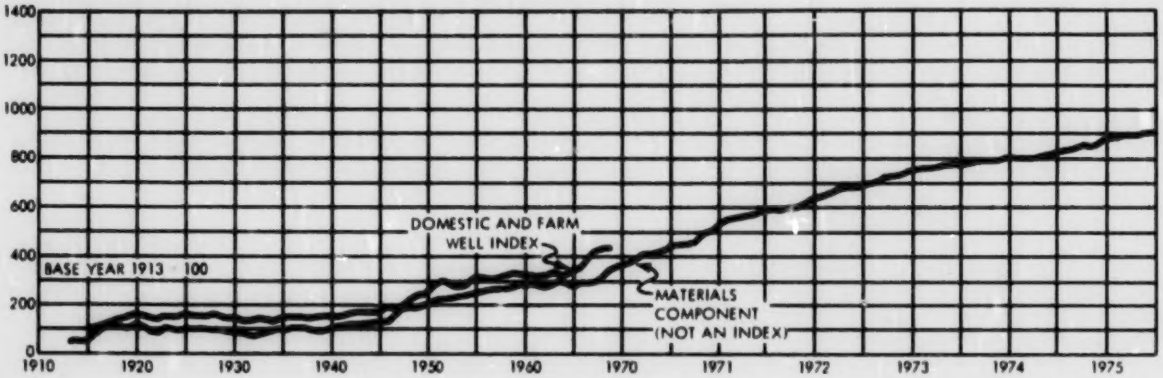

Figure 2. Small-diameter well costs index and the ENR materials component (after Gibb, 1971).

To update costs and to consider regional influences requires the formulation of multiplicative factors based upon the ENR indexes. These multiplicative factors can be formulated as simple ratios from graphical and tabular information. Figure 2 enables the determination of the materials component for any prior cost data back to 1913. Table 1, taken from the September 12, 1974 issue of ENR provides indexes on a monthly basis for 20 cities within the United States and the U.S. 20-city average index. At least 1 of the cities listed is found in each of the 10 EPA regions.

To apply the update method, the ratio of the materials component of the future date to the materials component of the date of the report cost data is required. The materials component associated with the report cost data can be obtained from Figure 2 or 3, depending upon the well size of interest. The materials component associated with the future date can be determined from the latest issue of ENR. Future costs as a national average can then be computed by multiplying the cost data given in this report by the computed ratio.

For example, assume that in May 1977 the estimated cost of 200 feet* of 8-inch diameter PVC pipe in Region VII is desired. From Table 10 (Section IV) it can be seen that the cost of the pipe is $1120 in Region IX in October 1974. Figure 2 shows the materials component for October 1974 as 850. Assume that the materials component of the May 1977 issue of the ENR shows an increase to 1300. The cost of the PVC pipe in 1977 is then determined by multiplying the October 1974 costs ($1120) times the ratio of the

---

*See Appendix for Metric Conversion Table.

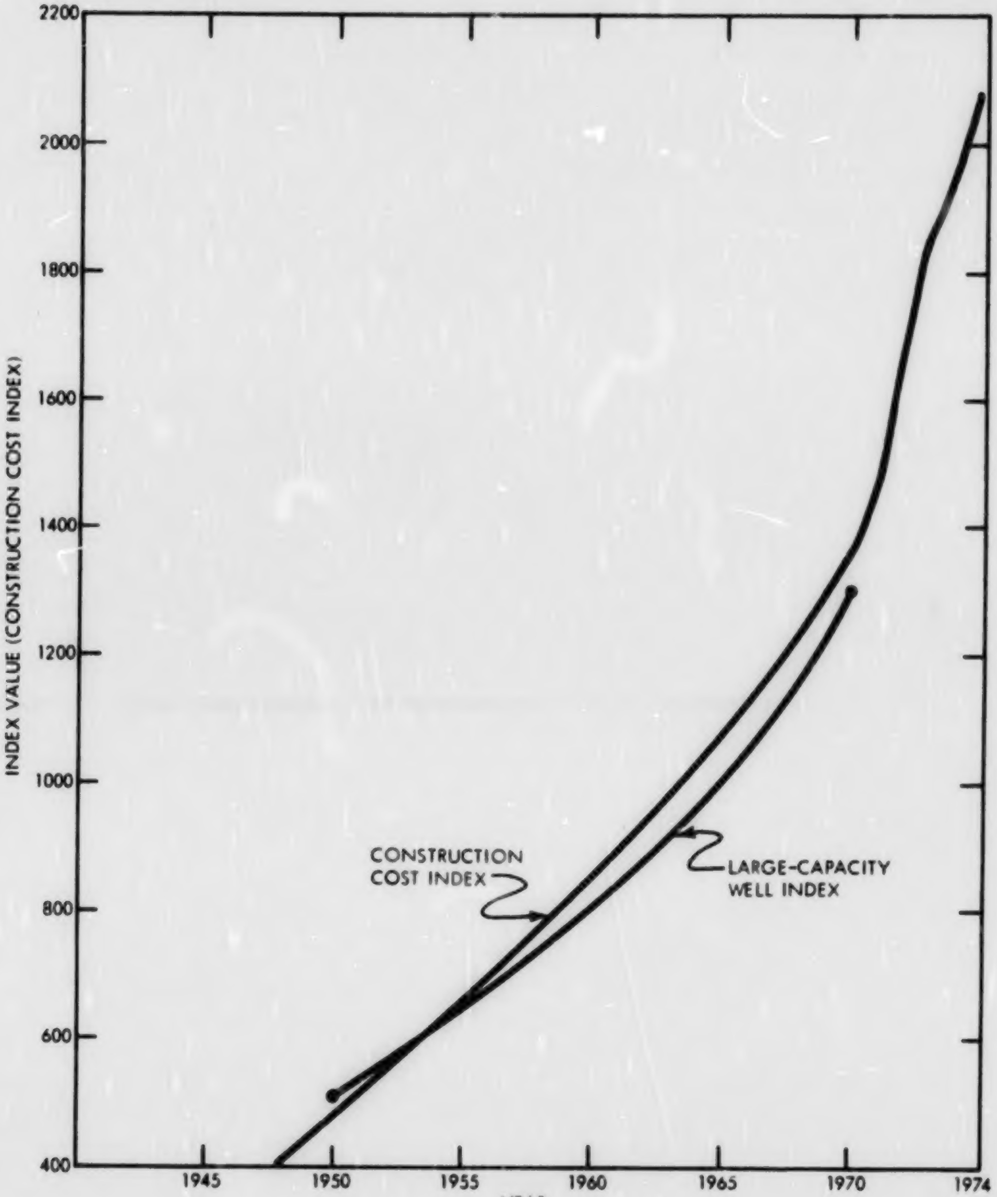

Figure 3. Large-capacity well costs index and the ENR construction cost index (modified after Gibb, 1971).

TABLE 1. EXAMPLE OF ENR INDEXES FOR SEPTEMBER 12, 1974

ENR COST INDEXES IN 22 CITIES
(based on 1913 U.S. average = 100)

City	Construction cost			Building cost		
	Sep 74 index	Percent change from last		Sep 74 index	Percent change from last	
		month	year		month	year
Atlanta	1,588.9	+0.2	+5.9	1,080.22	+0.3	+5.5
Baltimore	1,786.94	-0.9	+0.4	1,174.56	-0.7	+0.4
Birmingham	1,562.04	+0.8	+9.6	1,082.28	+1.7	+8.3
Boston	2,174.06	+0.2	+10.4	1,299.15	+0.1	+11.2
Chicago	2,205.91	-1.6	+5.4	1,296.94	-2.8	+6.1
Cincinnati	2,400.44	0	+9.5	1,328.34	-5.0	+9.8
Cleveland	2,375.78	-5.0	+8.5	1,312.39	-5.0	+7.2
Dallas	1,660.59	-0.5	+4.8	1,063.05	-0.8	+4.1
Denver	1,658.39	-0.3	+5.9	1,157.37	-0.4	+6.5
Detroit	2,387.69	-0.1	+7.1	1,341.53	-0.1	+7.4
Kansas City	2,261.63	-1.0	+9.2	1,240.71	-1.7	+7.0
Los Angeles	2,290.23	+6.7	+10.0	1,278.83	+3.1	+8.8
Minneapolis	2,093.94	0	+7.4	1,205.24	-5.0	+7.1
New Orleans	1,610.74	0	+9.4	1,104.52	0	+11.8
New York	2,568.37	+0.1	+6.6	1,461.86	+0.1	+6.8
Philadelphia	2,203.17	-1.0	+12.6	1,341.82	-1.6	+11.1
Pittsburgh	2,067.52	-0.1	+9.3	1,317.06	-0.2	+7.0
St. Louis	2,321.94	+0.2	+9.8	1,179.43	-0.6	+6.9
San Francisco	2,446.14	-0.2	+9.9	1,339.67	-0.4	+8.1
Seattle	2,111.96	+11.5	+14.5	1,149.32	+0.7	+12.2
U.S.—20 Cities' Average	2.088.82	+0.6	+8.3	1,237.71	-0.2	+7.6
Montreal	1,880.84	-5.0	+19.7	1,134.69	0	+21.5
Toronto	1,972.44	+0.4	+9.5	1,109.91	+0.5	+6.7

ENR WAGE, MATERIALS AND COST INDEXES IN 20 CITIES
(based on each city's 1967 average = 100)

City	Common labor		Skilled labor		Materials prices		Const cost index	Building cost index
	Sep 74 index	% change from Sep 73	Sep 74 index	% change from Sep 73	Sep 74 index	% change from Sep 73		
Atlanta	206.64	+7.7	185.86	+8.6	172.97	+1.7	195.30	180.01
Baltimore	229.39	+2.5	190.69	+4.2	175.14	-4.2	202.58	183.72
Birmingham	198.35	+12.3	193.45	+12.0	167.05	+4.0	187.22	180.28
Boston	205.36	+10.7	189.93	+12.3	187.44	+9.8	200.45	188.90
Chicago	193.79	+5.1	190.98	+5.8	155.14	+6.5	182.92	174.81
Cincinnati	233.59	+9.0	209.29	+8.6	197.42	+11.4	225.90	207.64
Cleveland	196.92	+8.7	193.91	+6.8	172.19	+7.8	169.60	184.62
Dallas	236.65	+7.1	186.50	+8.1	154.75	-0.5	210.14	175.98
Denver	177.88	+6.7	191.47	+8.4	163.37	+3.8	169.71	176.96
Detroit	201.72	+7.0	199.60	+7.3	157.23	+7.8	190.62	181.48
Kansas City	236.98	+9.4	206.37	+5.9	175.84	+8.4	218.67	191.59
Los Angeles	199.55	+7.9	192.14	+7.8	184.86	+10.3	194.24	185.76
Minneapolis	189.51	+7.0	184.24	+5.9	179.23	+8.6	182.61	174.93
New Orleans	199.27	+7.3	183.12	+9.8	181.03	+14.2	192.59	182.13
New York	180.36	+5.3	177.19	+4.2	194.83	+11.5	184.68	183.81
Philadelphia	220.00	+12.2	198.85	+9.4	200.34	+13.5	215.06	199.53
Pittsburgh	191.32	+9.3	183.56	+5.2	195.58	+9.4	185.77	178.83
St. Louis	198.70	+11.2	174.26	+8.4	171.32	+5.0	192.22	172.78
San Francisco	197.22	+10.4	181.24	+7.9	178.41	+8.4	193.25	180.05
Seattle	186.21	+14.9	176.39	+11.6	190.03	+13.1	187.08	181.82

1977 materials component (1300) to the 1974 component (850), or

$$\$1120 \times \frac{1300}{850} = \$1713 \quad ,$$

the approximate cost of the PVC pipe in Region IX in May 1977. To obtain the cost of the PVC pipe in Region VII would require a similar procedure using October 1974 and the May 1977 ENR cities material prices, an example of which is given in Table 1.

Regional variations can be handled in a similar manner. For example, in Table 1 the city which is closest in geographical location to the monitor well activity is identified. The index for this city divided by the U.S. 20-cities index gives a ratio. This ratio multiplied by the current costs as a national average provides the updated current costs for a given region.

Effects of Scale on Costs

Manufacturers generally offer discounts for large purchases or to preferred customers. Water well casing suppliers, for example, do not discount the price per foot of casing for the first 100 feet; however, discounts of 20 percent are common above a 100-foot purchase, and discounts of 30 percent are not uncommon on purchases above 1000 feet. Because pumps and grouting material are not purchased in large quantities for monitor wells, the effect of scale is small. Water analyses are subject to discounting on the basis of the number of routine tests performed on a sample rather than on the number of samples analyzed. As many chemical analyses require similar sample work ups, a routine or batch series of tests usually is considerably cheaper than the total for each of the tests performed individually.

In-House versus Out-of-House Costs

The internalization of costs within the Federal government and universities makes competition with commercial enterprises somewhat unbalanced. Subsidies to many Federal and State laboratories, for example, often are not reflected in water analysis prices. Federal government costs vary with and within agencies. By way of illustration, the Water Resources Section of the U.S. Geological Survey (USGS) has a water resource service geophysical facility that has one price for users within the USGS water resource sector, a second price for other USGS users, and a third price for Federal agencies such as the EPA. On the other hand, many monitoring functions performed within Federal agencies have one set price for all.

Accuracy and Costs

The cost of a monitoring method can vary with the accuracy of the technique. An aquifer model with 1000 nodes per unit area is much more expensive than a model with 10 nodes; the larger the model, the more accurate but also the more costly it is.

The accuracy of water quality analyses has become an increasing problem. Some parameters have accuracies established by the EPA, the Corps of Engineers, and local public health officials as well. Commercial laboratories performing water quality analyses usually report results in terms of 0.1 mg/liter (0.1 ppm). However, if accuracy to 0.01 mg/liter or greater is required, an additional charge of approximately one-third is added for each additional decimal point required.

SECTION II

MONITORING AT THE LAND SURFACE

INTRODUCTION

Groundwater monitoring programs have normally concentrated primarily on the saturated zone for indications of pollution. Too often, these programs have not considered the information that is available through analyzing the unsaturated zone and through monitoring of the land surface. In addition, surface water monitoring of recharge areas is only beginning to be recognized as a critical variable in pollution detection.

Monitoring of the land surface can be divided into nonsampling and sampling methods. The nonsampling methods can be further divided into waste-load inventory considerations, leaching potential calculations, pipeline and tank tests, artificial liner testing, aerial surveillance, and notification and emergency procedures. The sampling methods are divided into those for surface water bodies, wastewater, and solid wastes.

NONSAMPLING METHODS

Waste-Load Inventory

Identification of sources and methods of disposal are key items. An inventory of waste loads comprises data collection and tabulation of the volumes of liquid wastes and weights of solid wastes and their compositions. For most purposes, monthly data on volumes and weights will be sufficient, and in some cases annual data will suffice. Acquisition of these data is necessary as a basis for calculating the amounts of percolate that may occur and concentrations of pollutants in the percolate.

Data on the physical, chemical, bacteriological, and radiological characteristics of the wastes should be collected. For wastewaters, chemical analyses are almost always included. Records of temperature and density measurements are appropriate for cases where the wastewaters have characteristics greatly different from native groundwaters. Turbidity records are important in cases where the wastes bypass the topsoil, such as in disposal or injection wells. Bacteriological analyses are important in the case of disposal of human and/or animal wastes. Radiological analyses are of foremost importance in the cases of nuclear waste disposal and certain mining wastes, among others.

For solid wastes, data on the chemical, bacteriological, and radiological characteristics should be collected. Bacteriological analyses are important in the case of sewage sludge and certain animal wastes.

Calculation of Leaching Potential

One of the key portions of a groundwater pollution monitoring program is to calculate or determine the amount of water which percolates through the topsoil and is in transit to the water table. The water budget approach may be used, where the input at the land surface in the form of waste volume and precipitation are compared to the output, or evapotranspiration. For diffuse sources, such as return flow of irrigation water, annual values may suffice. If evapotranspiration exceeds the water input at the land surface, then no percolate may occur. For point sources where input may greatly exceed evapotranspiration, annual values may also be sufficient. However, monthly calculations are necessary where evapotranspiration is greater than the input on an annual basis, but the input is greater than evapotranspiration in some months. This is particularly true where most precipitation or much of the waste disposal occurs during a few months of the year.

Precipitation records are usually available for most areas or can be extrapolated. Evaporation from free water surfaces can be determined from measurements for land or floating pans (Harbeck et al., 1958; Kohler, 1954; Follansbee, 1933; Rohwer, 1933). Quite often these values are unavailable and measurements of pan evaporation must be made. Evapotranspiration in irrigated areas can be determined by a number of methods (Cruff and Thompson, 1967; Blaney and Criddle, 1962; Lowry and Johnson, 1942; Penman, 1948; Thornthwaite, 1948). The residual value, or percolation, is an important parameter, as it affects the subsequent dilution of wastes that occur in the aquifer. The value also is necessary as an index of potential pollutant load escaping the land surface.

Pipeline and Tank Tests

Recent studies (Osgood, 1974; U.S. EPA, 1974b) indicate that buried pipelines and storage tanks are potential sources of sewage, storm water, and petroleum product contamination. The volume of flow from these sources may be a secondary concern if the pollutant is of a toxic or noxious character. The major consideration is to determine if and where the system is leaking. Small leaks from service station storage tanks can release 15 to 20 thousand gallons of gasoline over time, without the operator being aware of his loss (Osgood, 1974). Since the threat of fire or explosion is of primary concern in oil and gasoline leaks, the National Fire Protection Association (NFPA) has been active in setting up monitoring programs. To date, the NFPA has not approved any pipeline tightness testing equipment although this equipment is being developed; it has endorsed one kind of tank tightness testing equipment.

Exfiltration and infiltration occurring in sanitary and storm sewers is a recognized engineering phenomenon. Where the system originally is poorly designed and improperly installed or where the pipelines are old and in disrepair, leakage of substantial quantities of poor quality water into the soil system can take place, eventually leading to contamination of groundwater. It is difficult to accurately determine the amount of leakage from these buried sanitary lines. The use of pressure in pipelines which are designed not to leak is a straightforward technique; however, these techniques are difficult to use in sanitary and storm sewers. The cost of performing a pipeline test would approximate the cost for a commercial tank test of the same volume.

In Maryland the county health departments reported 60 cases of pipeline and tank contamination in 1969-1970. These were detected from water in surrounding wells and not the sources, however. If it is possible to conduct input-output tests in sewer lines from basic flow data, large leaks may be detected. Large fluctuations in the flow received at the treatment plant which cannot otherwise be explained are another indication of leaks or breaks. However, in most cases the number of leaks in storm and sanitary drains will be large and individual losses will be low.

The testing of underground storage tanks can be done routinely. The Pennsylvania Department of Environmental Resources estimates that 2600 new or replacement subsurface storage tanks are buried in the ground in that State each year. If those replaced have failed, then this source of pollution deserves further monitoring. Most storage tanks are monitored using a calibrated "dip stick." This is a rough measurement, better than nothing, but not sufficiently sensitive to detect small leaks. The stick is usually read in the morning and evening and any difference indicates a possible leak. If a stick is not used, a manometer or float recorder may be used. These monitoring tools generally provide only rough approximations.

A more sensitive car-transportable tank tester, endorsed by NFPA, involves the use of a pressurizing device and a pressure loss recorder. The tank system tightness tester costs about $2875 FOB and is used by various consulting firms throughout the country. The average cost for an 8-hour (1 man-day) tank test is $300. Normally one man can operate the tester; however, he may need a pipefitter assistant under certain circumstances. The largest tank tested to date has a capacity of about 24,000 gallons. The cost of the tank test varies primarily with the size of the tank in question and the size of the leak. The average cost of on-site testing of various tank sizes is given in Figure 4. A tank with a bad leak may require only 15 to 30 minutes for leak detection after the tester has been set up, while a tight tank can require 3-1/2 to 4 hours. The time required to test a series of tanks or one large tank may be more than 8 hours. The rate charged usually does not vary and remains around $35-$40 per hour for both transportation

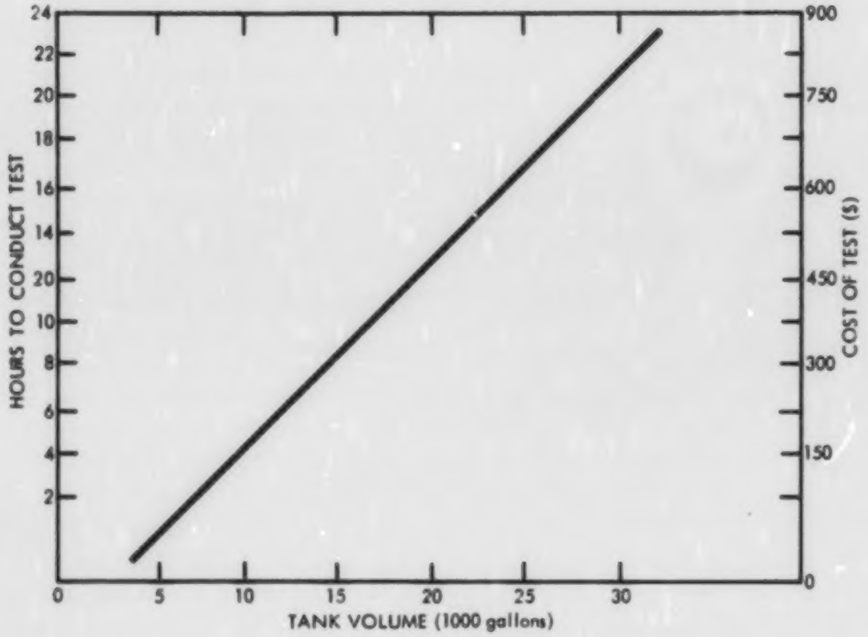

Figure 4. Cost of testing submerged tanks of various volumes, November 1974.

to the test site and actual testing. The test procedure can also be used to determine if water is seeping into the tank.

Tank testing has not been widely used, possibly through lack of awareness of the existence of test equipment. Owners have little legal responsibility to test their tanks. This situation may be compared to fire extinguishers, which are required by law and/or insurance companies to be routinely tested.

Tanks that have been abandoned by gas station operators, industries, etc. are of considerable concern. Many of these abandoned tanks still have hazardous materials in them and, if leaking, are potential pollution sources.

Testing Artificial Liners for Leakage

Large numbers of storage ponds and "evaporation ponds" leak and permit substantial quantities of pollutants to escape the land surface. Artificial liners are coming into wide use to limit such percolation. These liners may be made of compacted clay, plastic, rubber, concrete, bentonite, and other materials.

There are several ways to determine leakage. One method is to fill the pond prior to use with a liquid of like composition to the waste to be contained. Seepage can be calculated after precipitation and evaporation are determined. Another suitable test involves construction of a special collection device beneath the artificial liner. This is usually constructed by placing a relatively impermeable material several feet below the final liner. Drain pipes are then placed above the layer, on a grade toward a central collection point. Coarse-grained permeable materials are then placed in this interval beneath the artificial liner. These collection devices enable rather rapid determination of leakage from artificial liners. Seepage can also be calculated if the permeability of the artificial liner can be determined.

Aerial Surveillance

Aerial surveillance can be especially useful in land surface monitoring for groundwater pollution. Stockpiles, disposal and storage basins, and accidental spills can be seen from the air. Aerial surveillance can be used to determine what methods of disposal are being used under routine operation, as well as during accidents or unusual weather conditions. If, for example, sewage effluent is bypassing percolation ponds and flowing into a stream channel or canal this can be detected from the air.

In disposal operations such as mine tailing ponds, water may be present in the ponds as free water, moist tailings, or wet tailings. Since the calculation of percolation requires estimation of evaporation and the evaporation rate is different in each case, the relative concentrations of pond areas must be periodically determined. As many such ponds cannot be freely traversed on the surface, aerial surveillance is an important aspect. Photographs and visual observations from various directions and heights can provide useful information. Observations and surveys on the ground can be used as a control for the aerial surveillance.

Infrared photography is a proven tool in analysis of shallow groundwater conditions and phreatophyte growth. Cropping patterns and irrigation can also be analyzed. Chandler, Dowdy, and Hodder (1970) reported on the utility of aerial surveillance methods in water quality monitoring; however, most of their discussion was in reference to surface water.

Remote-sensing technology, usually in the form of aerial and satellite imagery, provides the land-use planner and manager with a new source of data. Remote sensing can be employed in a land-use planning program to: (1) provide an initial source of information, (2) identify the factors responsible for change in the resource base, (3) help define management policy, and (4) monitor the effect of these policies. In particular, septic field pollution could be determined from population estimates which in turn could be obtained from remote sensors. This estimate of population can be based on housing occupancy ratios and counts of houses. Another method involving remote sensing is sampling population densities per unit area of land-use classes and then using the total area of a given land use as the multiplier to calculate its total population.

In-house costs are minimized more in remote sensing than in any other groundwater monitoring technique. For example, the funding required to produce the ERTS-1 (Earth Resources Technology Satellite), Skylab, or a U-2 high-altitude sensor airplane are excluded from the purchase costs of raw data gathered by this equipment. In addition, Federal agencies such as the EPA and the USGS are active in remote-sensing research. The capital costs incurred by these agencies to develop a remote-sensing capability are difficult to determine; often only operational costs such as man-time, film, airplane fuel, etc. are charged for land-use surveys.

A few guiding principles in the use of aerial and remote-sensing surveys are:

- The larger the area, the less the cost per unit area for data acquisition and interpretation. This is true because the cost of mobilization is usually prorated on a per kilometer basis over the actual cost of acquisition, resulting in economies of size.
- In general, the higher the resolution, the larger the scale or the more specific the sensor, the higher the cost of acquisition, processing and interpretation. This suggests a multilevel approach beginning with large area, low resolution generalized coverage and proceeding to studies of selected smaller areas with more specific higher resolution techniques. At each level the available data should be exploited to the maximum degree possible before proceeding to the next step.
- Multipurpose or multiresource programs reduce the cost accorded to each end use. This follows because the costs of data acquisition, processing, and capital investment for interpretation can be shared among users.
- The cost of adding a sensor to an aerial platform is usually relatively small. Most of the cost of data acquisition is the cost of flying.
- Computer and computer-assisted interpretation becomes economical when large areas are covered, a large number of comparisons among several data types are required, and the decisions to be made are relatively simple. The same is generally true of other machine-assisted techniques.

Data acquisition and processing refer primarily to the imagery and tape costs. An example of the standard price list from the EROS Data Center, Sioux Falls, South Dakota is given in Table 2. Upon request the Center will provide a standard remote sensing order form. If the interpretation and verification capabilities are available, the cost of the EROS data is minimal. However, if interpretation and verification expertise is not available the

TABLE 2. EXAMPLE OF EROS DATA CENTER STANDARD COSTS—SATELLITE PRODUCTS, OCTOBER 1974

ERTS DATA

Image size (inches)	Scale	Format	Black & White unit price ($)	Color composite unit price ($)
2.2	1:3,369,000	Film Positive	2.00	NA
2.2	1:3,369,000	Film Negative	2.00	NA
7.3	1:1,000,000	Film Positive	3.00	12.00
7.3	1:1,000,000	Film Negative	3.00	NA
7.3	1:1,000,000	Paper	2.00	7.00
14.6	1:500,000	Paper	5.00	15.00
29.2	1:250,000	Paper	12.00	30.00

COLOR COMPOSITE GENERATION[a]
(when not already available)

Image size	Scale	Format	Unit price
7.3 inches	1:1,000,000	Printing master[b]	$50.00

COMPUTER COMPATIBLE TAPES

Tracks	Density (bits per inch)	Format	Set price ($)
7	800	4-tape set	200.00
9	800	4-tape set	200.00
9	1600	4-tape set	200.00

SKYLAB PHOTOGRAPHY

S190A image size (inches)	Scale	Format	Black & White unit price ($)	Color unit price ($)
2.2	1:2,850,000	Film Positive	2.00	5.00
2.2	1:2,850,000	Film Negative	4.00	NA
6.4	1:1,000,000	Paper	2.00	7.00
12.8	1:500,000	Paper	5.00	15.00
25.6	1:250,000	Paper	12.00	30.00

Notes:

[a] Color composites are portrayed in false color (infrared) and not true color.

[b] Cost of product from this composite must be added to total cost.

(continued)

TABLE 2 (Continued)

AERIAL MAPPING PHOTOGRAPHY

Image size (inches)	Format	Black & White unit price ($)
9	Film Positive	3.00
9	Film Negative	6.00
9	Paper	2.00
18	Paper	5.00
27	Paper	6.00
36	Paper	12.00
Photo Index	Paper	3.00

NASA RESEARCH AIRCRAFT PHOTOGRAPHY

Image size (inches)	Format	Black & White unit price ($)	Color unit price ($)
2.2	Film Positive	2.00	5.00
2.2	Film Negative	4.00	NA
4.5	Film Positive	2.00	6.00
4.5	Film Negative	4.00	NA
4.5	Paper	2.00	6.00
9.0	Film Positive	3.00	12.00
9.0	Film Negative	6.00	NA
9.0	Paper	2.00	7.00
9x18	Film Positive	6.00	24.00
9x18	Film Negative	12.00	NA
9x18	Paper	4.00	14.00
18.0	Paper	5.00	15.00
27.0	Paper	6.00	20.00
36.0	Paper	12.00	30.00

MISCELLANEOUS

	Black & White roll price ($)	Color roll price ($)
Microfilm		
16 mm (100-foot roll)	15.00	35.00
35 mm (100-foot roll)	20.00	40.00
Kelsh Plates		
Contact prints on glass. Specify thickness (0.25 or 0.06 inch) and method of	10.00	

(continued)

TABLE 2 (Continued)

MISCELLANEOUS (continued)		
	Black & White roll price ($)	Color roll price ($)
Kelsh Plates (continued)		
printing (emulsion to emulsion or through film base).		
Transformed Prints		
From convergent or transverse low oblique photographs	7.00	
35-mm Mounted Slide		
35-mm mounted duplicate slide where available	.60	

costs involved escalate rapidly. For example, the level of detail required may be Level I, II, or III. Examples of the kinds of detail observed at Levels I and II are given in Table 3.

A review of work by Sizer*, Simonett†, and Thorley (1973) for land-use mapping studies in the United States resulted in the cost figures for data acquisition, processing interpretation, and map preparation presented in Table 4.

The cost of a remote-sensing survey includes the costs of data acquisition, processing, interpretation, and verification. These costs in turn depend on the sensor or sensors used. Sensor selection must depend on the purpose and location of the survey, the areal size, the required level of detail, existing information on the area, the available facilities and equipment for processing and interpretation, labor availability and costs, platform availability costs, shipping costs, and for some surveys the time of year. Each of these factors can vary, which makes it impossible to define costs except in general terms.

Notification Procedures

Warning systems to protect against accidental spills have previously been developed by agencies other than those charged with groundwater quality

---

*Personal communication, 1973.

†Personal communication, 1973.

TABLE 3. LAND-USE CLASSIFICATION SYSTEM FOR USE WITH REMOTE-SENSOR DATA (Anderson et al., 1972; Poulton, 1972)

Level I		Level II	
01.	Urban and built-up land	01.	Residential
		02.	Commercial and services
		03.	Industrial
		04.	Extractive
		05.	Transportation, communications, and utilities
		06.	Institutional
		07.	Strip and clustered settlement
		08.	Mixed
		09.	Open and other
02.	Agricultural land	01.	Cropland and pasture
		02.	Orchards, groves, bush fruits, vineyards, and horticultural areas
		03.	Feeding operations
		04.	Other
03.	Rangeland	01.	Grass
		02.	Savannas (palmetto prairies)
		03.	Chaparral
		04.	Desert shrub
04.	Forest land	01.	Deciduous
		02.	Evergreen (coniferous and others)
		03.	Mixed
05.	Water	01.	Streams and waterways
		02.	Lakes
		03.	Reservoirs
		04.	Bays and estuaries
		05.	Other
06.	Nonforested wetland	01.	Vegetated
		02.	Bare
07.	Barren land	01.	Salt flats
		02	Beaches
		03.	Sand other than beaches
		04.	Bare exposed rock
		05.	Other
08.	Tundra	01.	Tundra
09.	Permanent snow and icefields	01.	Permanent snow and icefields

TABLE 4. TOTAL COST OF AERIAL SURVEILLANCE FOR LAND-USE MAPPING, JULY 1974

Level of detail	Scale of final product	Method or basis	Data sources	Cost/km^2 ($)
Level I	1:250,000 to 1:500,000	Satellite imagery	1:250,000 ERTS imagery	0.15 - 0.27
		High-altitude aircraft imagery	1:50,000 aerial photographs	2.00 - 3.60
Level II	1:250,000 to 1:63,360	Satellite imagery only	ERTS imagery	0.25 - 0.45
		High-altitude aircraft imagery	1:90,000 aerial photography	2.25 - 4.05
	1:63,360	Multiscaled approach	ERTS imagery, high-altitude aircraft photography and ground truth	0.75 - 1.35
Level III	1:24,000 to 1:63,360	Commercial	Relys on 1:90,000 high-altitude photography	2.75 - 4.95
	1:12,000 to 1:40,000	Commercial	1:24,000 aerial photography	5.75 - 10.35

control. The major agency responsible for control of these spills has been the Department of Transportation. Apart from their other effects, spills of very short duration, such as hours or days, can result in groundwater pollution for decades or longer. Thus, prompt action is necessary, and advance warning of potential problems can be given by established notification procedures. However, notification procedures for hazardous substance transportation are poorly documented in most States and nonexistent in others. Notification procedures require that a responsible body be notified when any hazardous materials are to be moved. The intent is to insure that when they are transported through a certain area the full potential of the danger involved is realized and that emergency crews are alerted in case of an accident. Of more importance, however, is the assurance that those doing the transporting will abide by safety regulations governing the move.

The majority of the States do not have a notification procedure tied into their groundwater monitoring program, and thus basic cost data are not available for warning systems and notification procedures. It is estimated that a notification monitor would approximate a safety inspection officer in training and salary, with the latter ranging from $10,000 to $15,000 per year.

Although transportation of hazardous substances can be by boat, rail, highway, air, or pipeline, the regulations for highway transportation are perhaps the most relevant to groundwater problems. The majority of the manpower required for notification procedures usually falls outside a monitoring agency's responsibility. The person charged with monitoring the procedure, however, should spot check to see that notification procedures are followed.

The best form of notification procedure is a specific permit to transport hazardous substances. These permits should be based upon applications submitted to a Transportation Board. An application for hazardous material permit should include the following:

- Name and address of applicant
- Business of applicant
- Requested exemptions to regulations
- Reason a specific permit is required
- Points of origin-destination and proposed routes
- Evidence to establish that transportation can be accomplished without undue hazard to public health and safety
- Period during which permit is to be effective
- Additional information as may be required.

The Transportation Board should then determine if a permit is required. If a permit is needed it should:

- Describe the situation to which the permit applies
- Authorize such exemptions as may be warranted
- Establish the period of time in which the permit is effective
- Impose any new or special conditions which must be observed.

With the establishment of a permit system, a set of rules must be established for both shipper and carrier to cover the safety aspects required by the permit. The rules and regulations for the shipper could specify acceptable containers, marking, labeling, etc., whereas those for the carrier should specify loading and unloading and vehicle operation procedures, driver qualifications, etc.

The person charged with monitoring the notification procedures would check both shippers and carriers according to some sampling schedule to see that the rules and regulations were being followed. The monitoring could involve a review of a few permit applications that were accepted. Follow-up inspections could be done to see that proper containers were used and that the labeling was sufficiently clear. In addition, those permit applications that were turned down could be investigated to determine if potentially dangerous materials were still being transported. Carriers could be monitored for fully operational vehicles. In addition, drivers' logs could be reviewed for compliance with prescribed driving periods.

The transportation of hazardous material by highways is but one example of the kind of notification monitoring that could be implemented. Currently this type of monitoring is relatively rare; however, the reason primarily has been a lack of rules and regulations on the handling of hazardous materials. Many States currently are developing legislation to cover the transportation and monitoring of hazardous materials.

Emergency Procedures

Emergency procedures to cover accidents once they have occurred are generally well defined. City and State police officials as well as Department of Transportation personnel are informed as to procedures to follow when an accidental spill occurs. The time required to correct the damage is very important because if the material seeps into the soil subsurface excavation can be costly. The emphasis, therefore, is on quickly reaching the site and taking action to minimize the infiltration and contamination of the soil matrix. The role of monitoring under these circumstances is to insure that the emergency procedures are operational and that responsible personnel and equipment are ready to react to a call. This monitoring responsibility may be compared to that of a fire inspector who is charged with insuring that fire-fighting equipment is ready should an alarm be sounded.

Many States have a disaster office which controls emergency procedures for hazardous material spills. In the event of a hazardous substance spill or serious threat of such a spill, warnings should be given to endangered persons, to local authorities, and to the State Disaster Office (Figure 5).

Regardless of the makeup of the organization or the type of location of a spill, certain basic operations must be carried out. The employment of any or a combination of the suggested measures can be undertaken only after technical advice has been sought and safety, feasibility, availability of material and equipment, side effects, and consequences have been considered.

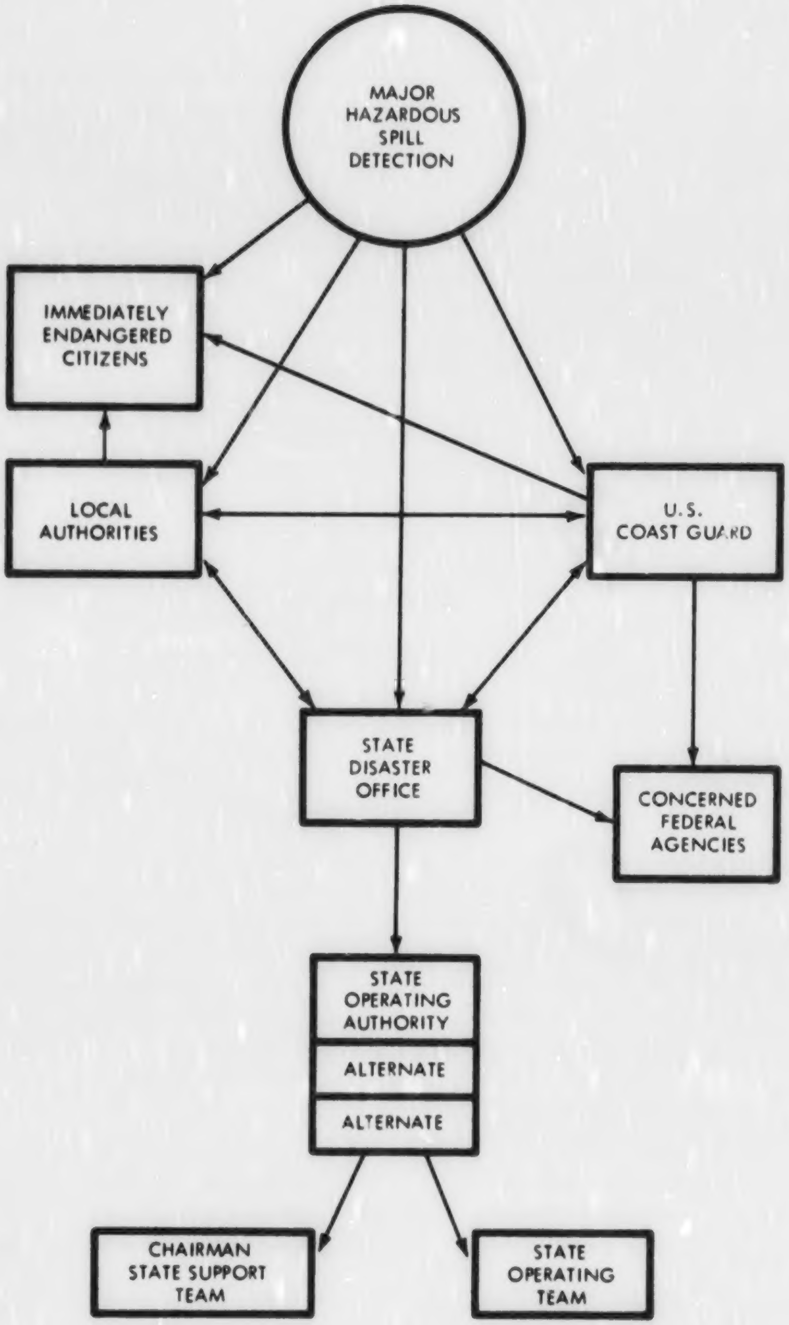
MAJOR HAZARDOUS SPILL DETECTION
IMMEDIATELY ENDANGERED CITIZENS
LOCAL AUTHORITIES
U.S. COAST GUARD
STATE DISASTER OFFICE
CONCERNED FEDERAL AGENCIES
STATE OPERATING AUTHORITY
ALTERNATE
ALTERNATE
CHAIRMAN STATE SUPPORT TEAM
STATE OPERATING TEAM

Figure 5. Alerting procedure chart for hazardous material spills (after California Emergency Plan, 1970).

Some of the following operations may be conducted a step at a time, but many will of necessity be carried out simultaneously.

- Issue warnings and establish patrols
- Establish operations center
- Gather information
- Secure spill
- Containment, removal, and disposal of material
- Cleanup and rehabilitation of area.

All of the above operations require logistic support such as provisions, materials and equipment, transportation, loading, unloading and storage facilities, and security provisions for same; communications; personnel; sampling and analysis; equipment maintenance; medical services; collection and recording of data (including photography) on a day-to-day basis; legal counsel; and administration, record keeping, funding, and accounting.

The cost of monitoring the emergency procedures consists primarily of the salary and travel expenses of an inspector. The inspector can check to see that each person involved is aware of his responsibilities and that all equipment is ready for mobilization. Through a sequence of phone calls, personal visits, and actual equipment testing, the inspector can determine if the emergency procedures are workable. An inspector's training would often be derived from industrial safety programs rather than from a county or State program.

SAMPLING METHODS

Surface Water Bodies

Surface water sampling includes rivers, lakes, estuaries, and canals that are sources of groundwater recharge. Of primary concern are polluted surface waters. Precipitation should also be sampled in areas where it directly recharges the groundwater. Surface water sampling will be conducted through federally mandated monitoring programs (U.S. EPA, 1974b), but additional monitoring will be necessary in some areas to evaluate polluted recharge. Sampling of surface water has been discussed by Hem (1970), and Brown, Skougstad, and Fishman (1970).

To adequately determine the composition of a flowing stream, each sample, or set of simultaneous samples, must be representative of the entire flow at the sampling site at that instant. Furthermore, the sampling process must be repeated frequently enough to define changes with time that occur in the water passing the sampling point. For most streams, one sample cannot be safely assumed to represent the water composition closely for more than a day or two and for some streams not for more than a few hours. If the average composition of the whole flow of the stream, or its changes in composition over a period of time, are factors of principal significance, sampling locations where mixing is incomplete should be avoided.

Daily sampling is generally believed to provide a reasonably complete record for most large rivers. Composited daily samples can be used to calculate mean annual chemical composition of streamflow and total loads of dissolved solids carried with reasonable accuracy. For many kinds of water-quality studies, however, compositing of samples is not desirable. As automated or continuous-recording equipment for conductivity and other variables comes into wider use, properly designed supplementary sampling and chemical analyses will provide many details on water-quality regimes which are not attainable by daily sampling alone. Discharge or flow measurements should be available for sampling sites.

Water stored in lakes and reservoirs commonly is poorly mixed. Single samples from lakes or reservoirs can be assumed to represent only a single location within the water body.

The EPA (U.S. EPA, 1974b) has summarized rules for intensive monitoring of navigable waters. Station locations, parameter coverage, and sampling frequencies are considered. Monitoring stations should be located so as to measure inputs, transformations, movements, and outputs of pollutants within a given survey area.

The physical, chemical, biological, microbiological, hydraulic, hydrologic, climatic, and geometric parameters to be measured during monitoring surveys will depend upon the survey purpose and local conditions, and should be tailored to the specific pollution problems of the area. Sampling frequencies must be determined on the basis of variability of each of the parameters associated with the pollution problem, and must be adequate to define the pollution problem within statistically determined confidence intervals. The sampling frequencies must be adequate to determine mass balances of pollutants where necessary to define fluctuations of water quality and related parameters in receiving waters and pollutant sources.

Portions of surface water bodies can be selected for detailed sampling in areas where groundwater recharge is significant. This determination can be made on the basis of surface water budget analysis, groundwater level contour maps, and interpretation of soils and hydrogeological factors. It may be desirable to locate surface water sampling sites near wells or other groundwater monitoring facilities in some cases.

Wastewater

The American Public Health Association (1971) reported on the collection of samples of domestic and industrial wastewaters for physical and chemical analyses. Only representative samples should be used for analysis, but the great variety of conditions under which collections must be made precludes prescription of a fixed procedure. In general, the sampling procedure should take account both of analyses to be made and the purpose for which samples are taken.

When testing for average concentrations, a 24-hour composite sample is considered standard for most determinations. When the purpose is to show peak concentrations, the duration of peak loads, or the occurrence of variations, grab samples collected at suitable intervals, and analyzed separately, are more appropriate. The sampling interval should be chosen on the basis of the frequency with which changes may be expected, and may vary from as little as 5 minutes to as long as an hour or more. Under other circumstances, a composite sample representing one work shift or less or a complete cycle of a periodic operation may be required. Evaluation of the effects of special, variable, or irregular discharges and operations may require composite samples representing the periods during which such wastes are present.

Composite samples cannot be used for analysis of constituents which are subject to significant and unavoidable changes when stored. Such determinations should be performed on individual samples as soon as possible after collection, preferably at the sampling point. Analyses for all dissolved gases, residual chlorine, soluble sulfides, temperature, and pH are examples of determinations of this type. Additional details are given by the American Public Health Association (1971), part 200, the American Society for Testing Materials (1969), and EPA (U.S. EPA, 1972, 1973, 1974a). Current articles in the Journal of the Water Pollution Control Federation commonly discuss wastewater sampling.

Two basic categories of wastewater sampling relate to groundwater pollution. The first is that of the discharge stream at the point of wastewater discharge. In some cases the discharge stream contains solids as well as liquids. This type of sampling has been common, especially in cases where treatment plant performance is being evaluated. The second category is sampling in percolation ponds and other types of ponds which may leak. For monitoring groundwater pollution, the sampling of pond waters is often direct and often requires either construction of special walkways or the use of boats for sample retrieval. In others, where water is recycled, collection devices allow relatively easy sampling.

Of extreme importance is an understanding of how the wastewater is generated. For example, in sampling mine tailings pond wastewater a knowledge of what reagents are added at the mill, the type of ore being processed, and any unusual occurrences is necessary to correctly interpret the results. In sampling open waters, climatic factors such as rainfall and temperature are very important. Consideration should be given to groundwater recharge in the selection of sampling sites. Thus, wastewaters overlying more permeable soils and sediments should deserve primary attention.

Generally a 3-liter Kemmerer or Van Dorn style water sampler costing from $120 to $200 is used to sample surface water bodies. The cost of sampling varies primarily with the time required to obtain the samples. Travel time and mileage to the site must be added to the time spent sampling the water body. Provided a small boat and motor are available, one man can sample up to about 50 locations per day in an average mine tailing pond. The sampling time at each location depends primarily upon the depth from which the sample must be retrieved. A 3-liter sample hand-drawn from about 20 meters requires about 5 minutes.

In a river or a long reservoir, the distance between sample locations becomes important. Assuming that the boat must return to its original position, samples from 15 to 25 locations over a 25-mile stretch can be taken in 1 day. If wastewater or solid waste samples are to be taken from point sources, the travel time and mileage between the locations may be the principal governing cost factor.

Solid Wastes

The chemical composition of many solid wastes can be categorized on the basis of past experience and available data in the literature. For point source solid wastes, sampling at the land surface is confined to occasional samples of the waste for analysis. The primary monitoring in this case is an inventory of the weight or volume of waste. For diffuse sources of solids, the main monitoring involves a complete inventory of amounts being applied on an annual basis. Monthly or weekly data may be necessary in some cases, such as the application of nitrogen fertilizers, where the amount leached will vary seasonally depending on crop uptake of nitrogen, temperature, irrigation applications, etc.

SECTION III

MONITORING IN THE VADOSE ZONE

INTRODUCTION

Topsoil

The topsoil is the region that manifests the effects of weathering of geological materials, together with the processes of eluviation and illuviation of colloidal materials, to form more or less well developed profiles (Simonson, 1957). Water movement in the topsoil usually occurs in the unsaturated state, where soil water exists under less-than-atmospheric pressures. The physics of unsaturated, soil-water movement have been intensively studied by soil physicists, agricultural engineers, and others. Copious literature is available on the subject in periodicals (*Soil Science Society of America Proceedings*, *Soil Science*, and *Journal of Environmental Quality*) and textbooks (Childs, 1969; Kirkham and Powers, 1972). Saturated zones may develop over horizons of low permeability. A number of books are available on the theory of flow in perched water tables (Luthin, 1957; van Schilfgaarde, 1974). Soil chemists and soil microbiologists have also attempted to quantify the chemical-microbiological transformations during soil-water movement (Rhoades and Bernstein, 1971; Dunlap and McNabb, 1973).

Vadose Zone

Weathered materials of the topsoil gradually merge with underlying materials such as igneous or metamorphic rocks, alluvium, lake deposits, eolian deposits, or lacustrine beds. The region beneath the topsoil and overlying the water table, where water exists primarily in the unsaturated state, is known as the vadose zone. Perched water tables may develop above interfaces between layers having greatly different textures. Saturated conditions may also develop beneath recharge sites as a result of prolonged infiltration. In contrast to the large number of studies on water movement in the topsoil, parallel studies in the vadose zone have been few. Meinzer (1942) coined the term "no-man's land of hydrology" to describe the limited knowledge of this zone.

Monitoring Techniques

A number of techniques have been developed for monitoring water movement and water quality in the topsoil. Detailed descriptions, specifications, and methods of many of these techniques were compiled in American Society of Agronomy Monograph No. 9, "Methods of Soil Analysis" (Black, 1969). Monitoring in the vadose zone requires an extension of topsoil monitoring technology. Examples are available where this approach has been used; Apgar and Langmuir (1971), for example, successfully used suction cups, developed for sampling soil solutions, to sample at depths up to 50 feet below a sanitary landfill. Of primary interest are flow rates to the water table and the storage capacity of the materials above the water table.

Water Content

Soil and underlying geologic materials consist of a solid and porous matrix. Porosity is a measure of the amount of water which could be stored by the materials under saturated conditions. Field capacity of a soil is represented by its water content (on a dry weight basis) at a certain time after the initiation of drainage following an irrigation cycle (Peters, 1965). The definition of specific retention for geologic materials is essentially the same. except that the water content is expressed on a volumetric basis. Specific yield or effective porosity of geologic materials is the difference between porosity and specific retention. At a given time, the volumetric water content of a material is a reflection of various forces acting on the soil-water system, including gravity, capillary, and osmotic forces. Soil-water pressure is a measure of capillary forces and is expressed in terms of negative pressure; the relation between water content and pressure may be determined in the laboratory. This relation is essential to calculate water flow rates in the vadose zone.

Water Flow

Infiltration is the movement of water across the soil surface from an applied water source. Factors affecting infiltration capacity, or the maximum rate of infiltration, include soil texture, initial water content, and soil stratification. Determination of the rate of water flow out of a given soil depth may be determined from sequential drainage profiles (curves showing the relation between soil depth and water content for various times after the cessation of infiltration). The salinity and composition of the solution may have a pronounced effect on water movement.

For saturated materials the pressure is positive and measured by piezometers. For unsaturated materials the pressure is negative and measured by tensiometers.

Chemical Changes

The interactions of infiltrating water and soil have been reviewed by Ellis (1973), Rhoades and Bernstein (1971), Murrmann and Koutz (1972) and McNeil (1974). Among the main reactions are: precipitation, dissolution, ion exchange, adsorption, and oxidation-reduction.

Changes in the concentration of a soil solution following surface application include water removal by evaporation and transpiration. Precipitation of slightly soluble salts, primarily calcium carbonate or calcium sulfate, may occur as the soil solution is concentrated during evapotranspiration. Dissolution of soil minerals contributes to the salinity of the soil solution. Ion exchange represents an important soil-water interaction for altering the composition of the soil solution. Ion exchange is a function of the cation exchange capacity of the soil, which in turn is related to colloidal clay minerals, soil organic matter, iron and aluminum sesquioxides, and hydrous oxides.

Adsorption of metals onto the surface of soils is the most important process for removing some chemicals from wastewater (Murrmann and Koutz, 1972). In contrast to ion exchange, in which ions retain their mobility, in adsorption reactions ions are held so tightly that they become essentially immobile. Methods to quantify the extent of adsorption of ions onto solids have been developed. Oxidation and reduction reactions are of special importance in the case of sulfur and nitrogen compounds in water, as well as for many trace elements. These reactions affect the mobility of some elements and may result in the production of gases which can be lost from the soil-groundwater system.

SOIL SAMPLING AND WELL DRILLING

A test drilling program may be necessary to supplement existing data on the vadose zone at a site. Soil sampling and well drilling are generally necessary for all types of monitoring in the vadose zone. Test wells can also function as observation wells, piezometers, or access wells.

Shallow Wells

In general, samples from the soil zone are obtained to (1) characterize the average soil texture, water content, or chemistry in depth increments (e.g., 15 cm), (2) observe the precise depth distribution of soil texture, or (3) determine the bulk density, or water-release curves, of soil increments. For the first purpose land samplers such as post-hole augers, screw or sleeve type augers, or power-driven augers are useful. For the second purpose, cores are obtained by driving small-diameter (e.g., 2.5 cm) tubes into the soil to the desired depth. For the third purpose, larger diameter core samplers are used—these may be hand-driven or power-driven. Cores of a specific volume are obtained by each method. More information on coring is presented by Blake (1965).

The cost of a "bucket" type hand auger is about $35. These augers are available to cut core sizes from 2 to 4 inches in diameter. Four-foot extensions for deeper sampling cost about $6 each. For deeper samples a hand-driven soil sampler system can be purchased. These systems include soil sampling tubes, a drop hammer, and a tube puller jack to withdraw the tubes. The soil sampling tubes vary from 4 to 16 feet in length and cost from $65 to $115, respectively. The cost of the hammer and puller jack is about $200.

Deeper Wells

To sample throughout the vadose zone it may be necessary to drill deep wells using standard techniques. Such techniques include jetting, rotary, cable tool, augering, and air drilling. Of these methods perhaps augering, using continuous flights, and air drilling provide the most usable samples—problems develop in characterizing the distribution of indigenous salt and water content with cable tool and rotary methods because of water additions during the drilling process. The cost of power-augering multiple depth and density holes is given in Figure 6. These augering costs are developed for 8-inch diameter holes.

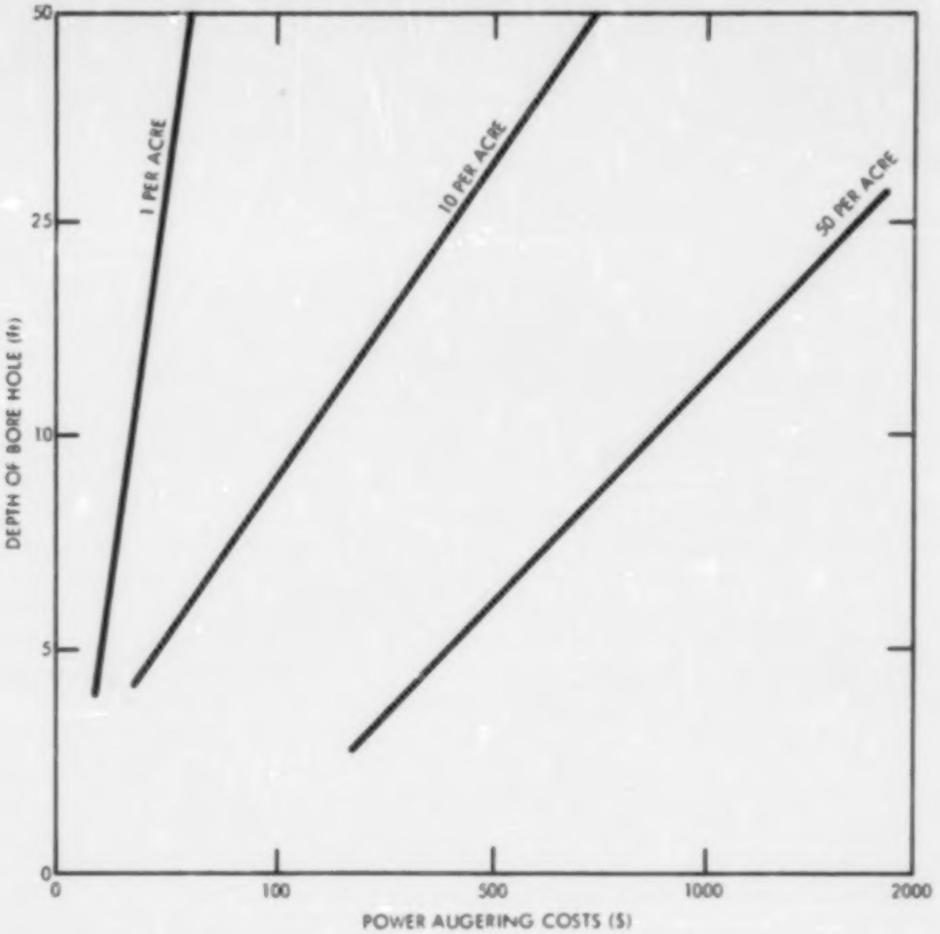

Figure 6. Cost of power-augering 8-inch diameter sample holes to various depths and hole densities, November 1974.

One air-drilling technique (Becker Drills, Inc., Denver, Colo.) involves driving a double-wall tube by a pile hammer while concurrently forcing air under pressure down the annulus of the pipe. Air and entrained material cut by the bit return to the surface through the inside pipe. The sample, available continuously, is diverted into a cyclone sampler where it is bagged for laboratory analyses. Changes in formation can be determined within a few centimeters; furthermore, water seams can be determined immediately. This feature is advantageous in locating the depth and thickness of perching layers. Whichever technique is used, samples should be taken in specified increments throughout the vadose zone.

DETERMINATION OF WATER CONTENT

Although a major concern of a monitoring program may be the movement of water in the vadose zone, it is also important to account for the storage capabilities of this zone. In western valleys with deep alluvium the vadose zone may constitute a vast reservoir for such in-transit storage.

Examining this water content requires the extension of techniques employed in the soil zone downward to the water table. Fortunately, many of the methods may also be used simultaneously to monitor water movement.

Neutron Moderation or Moisture Logging

For many years agriculturists have employed the principle of neutron moderation or thermalization to measure the volumetric water content of soils in situ. Recently, the technique has been used to monitor water storage in the vadose zone, particularly to delineate perching layers and mounds, and also to estimate flow rates.

The method of water content evaluation by neutron moderation depends on two properties relating to the interaction of neutrons with matter: scattering and capture (Gardner, 1965). High-energy neutrons, emitted from a radioactive source are slowed down, or thermalized, by collisions with atomic nuclei. Hydrogen has a greater thermalizing effect on fast neutrons than occurs with many elements commonly found in soils. This forms the basis for detecting the concentration of water in a soil (Van Bavel, 1963). The second property of interest in the neutron moderation method is capture of slow neutrons by elements present in the soil with the release of energy. The property of energy release during capture serves as a means of detecting the concentration of slow neutrons.

When a source of fast neutrons is lowered into a soil through a suitable well bore or casing, a cloud of thermalized neutrons is established. If a suitable calibration is made to isolate the moderating effects of soil nuclei other than hydrogen, changes in the volume of the thermalized cloud will reflect changes in water content. Finally, a detector which relies on capture of thermalized neutrons is used, in conjunction with suitable electronic circuitry, to measure the water content (on a volume basis).

Instrumentation used to measure water content by neutron thermalization requires three principal components: (1) a source of fast neutrons, (2) a detector of slow neutrons, and (3) an instrument to determine the count rate from the detection equipment, as shown in Figure 7.

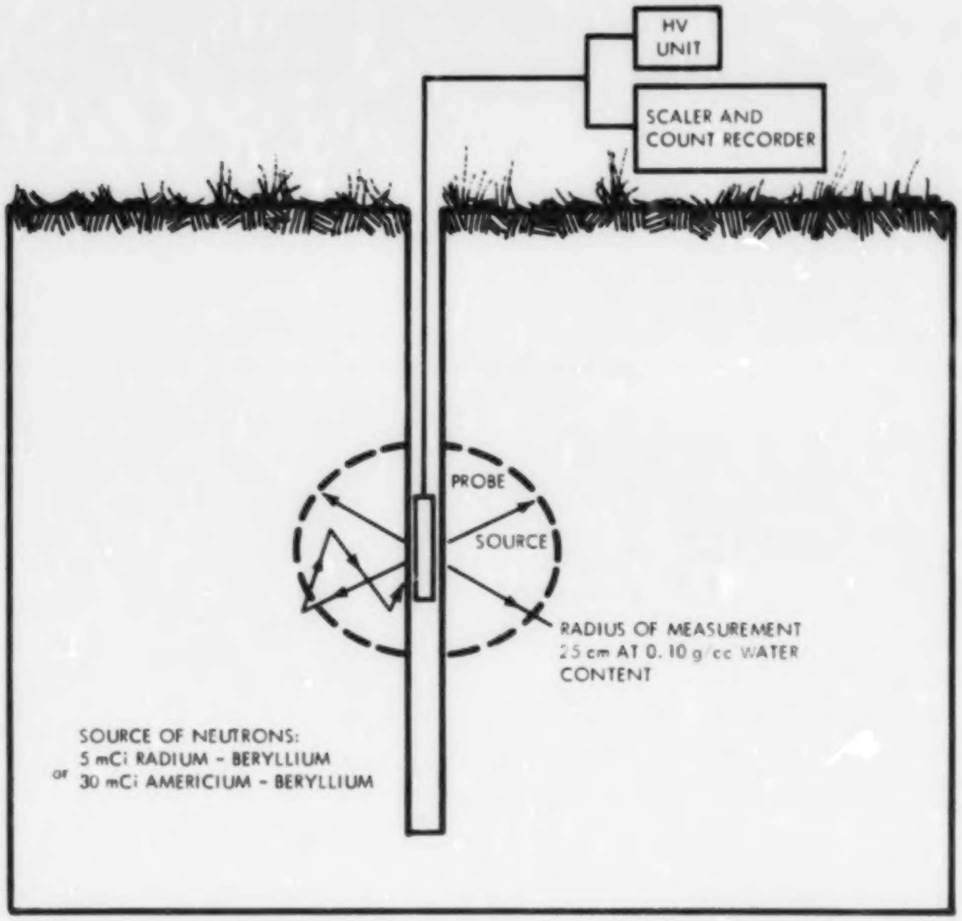
HV UNIT
SCALER AND COUNT RECORDER
PROBE
SOURCE
RADIUS OF MEASUREMENT 25 cm AT 0.10 g/cc WATER CONTENT
SOURCE OF NEUTRONS:
5 mCi RADIUM - BERYLLIUM
or 30 mCi AMERICIUM - BERYLLIUM

Figure 7. Sketch of neutron moisture logger and accessories (after Holmes et al., 1967).

Americium-beryllium is commonly used as a source of fast neutrons. Detectors of slow neutrons rely on high capture cross sections of detecting materials (e.g., boron). A charged particle is emitted during capture, which can be detected by a solid or gaseous counting device. The predominant detector is lithium-enriched BF_3. Both the source and detector are located in a cylindrical probe, or tool, which is lowered via a cable into access tubing either by hand or by motor-drive. The depth of measurement is determined by graduations on the cable or, alternatively, by some type of counter (Van Bavel, 1963).

The pulse emitted during the nuclear reaction resulting from capture is amplified within the down-hole tool and transmitter through the cable to an above-ground meter for counting. Count rate is converted to water content via suitable calibration curves. The type of equipment that has been available for soils work is hand operated. Its use requires placing the down-hole tool at a discrete depth, taking a count or number of counts, and then moving the tool by hand to another discrete depth. This process is not troublesome for shallow soils studies. However, for deeper access wells, in the vadose zone, an inordinate amount of time would be involved. Recently, a motorized unit became available (Well Reconnaissance of Dallas, Texas) which permits lowering the tool in the well at a constant rate, via a motor drive. Internal electronic components concurrently translate pulse rate into water content, which is automatically recorded.

The individual neutron moisture logger should be calibrated against samples of known water content. Such calibration may be done in the field by comparing a count at a given soil depth with the water content of soil cores from the same depth.

Access tubes for neutron moisture logging are usually constructed of seamless steel or aluminum. Polyvinylchloride-cased wells may cause difficulty in that hydrogen or chlorine atoms in the tubing may moderate the thermal neutrons, interfering with soil moisture evaluation. Aluminum-cased wells may deteriorate in saline groundwaters. The inside diameter of wells should be as close as possible to the outside diameter of the probe. Work by Ralston (1967) showed that for a 100-millicurie (mCi) Am-Be source in a 3.8-cm OD tool, the water content could not be accurately evaluated in well casings with an ID greater than 10 cm.

Wells drilled for shallow water content monitoring can be easily installed by successively augering and driving the tube. Myhre et al. (1969) reported on a simple power-driven auger for installing wells to 150-cm depths. For deeper wells standard drilling techniques are necessary. During installation by drilling techniques it is essential to establish a tight fit between the well shaft and casing, to minimize the amount of vertical leakage of water. Drilling mud, although facilitating the drilling operation, is not recommended since it interferes with water content observations. In situations requiring a tight fit, drilling techniques which do not require a drilling mud (jetting, augering) are used.

The principal advantage of neutron moisture logging is that water content profiles are obtained in situ with minimal soil disturbance. A history of profiles can be established during a monitoring program. Moisture logs clearly show the presence of perched water tables, together with their growth and dissipation (see Figure 8). Such logs may also be used to estimate unsaturated flow rates. Water content exchanges at a given depth in a succession of wells may provide clues on lateral flow velocities (Wilson, 1971).

Certain limitations should be noted. First of all, the presence of excessive concentrations of other fast neutron moderators (e.g., boron, chlorine) may cause erroneous water content determinations. Neutron moisture logs indicate only the water content of soils, and may not always manifest water movement. However, water content values may be translated to equivalent soil-water suction values via a soil-water characteristic curve.

The cost of a neutron moisture logger including the neutron source, slow neutron detector, and surface counter is about $3000. Figure 9 gives the cost of neutron moisture logging with various numbers of well loggings performed at depth intervals of 2 feet. The costs in Figure 9 do not include the capital cost of the instrument, but only the time required to conduct the log.

Tensiometers

Tensiometers are used to measure soil-water pressures during unsaturated flow. If caution is exercised, they may also provide estimates of soil-water content via suitable soil-water characteristic curves. Basically, a tensiometer consists of a porous ceramic cup cemented to a rigid plastic tube, small-diameter tubing leading to a manometer and terminating in a reservoir of mercury, and a filler plug in the rigid plastic tube (see Figure 10). Except for the reservoir and the portion of the small-diameter tubing filled with mercury, the internal volume of the system is completely filled with water. When properly emplaced in the soil the pores in the cup form a continuum with the pores in the soil. Water moves either into or out of the tensiometer system until an equilibrium is attained across the ceramic cup. The mercury level in the manometer tubing adjusts correspondingly.

Holmes et al. (1967) have noted the precautions to be taken during installation of tensiometers. Prior to field installation, the system should be purged of as much entrained air as possible and its response checked. The tensiometer unit should be placed into soil cavities larger than the outside diameter of the unit. The cup should be forced into the soil at the base of the hole to ensure good contact. The hole is then backfilled with soil.

The principal limitation of tensiometers is that they are useful in measuring soil-water pressures only up to about 1.0 atmosphere. Furthermore, the determination of water content via tensiometer values is subject to hysteresis: i.e., different water content versus pressure curves will be followed depending on whether the soil is wetting or drying.

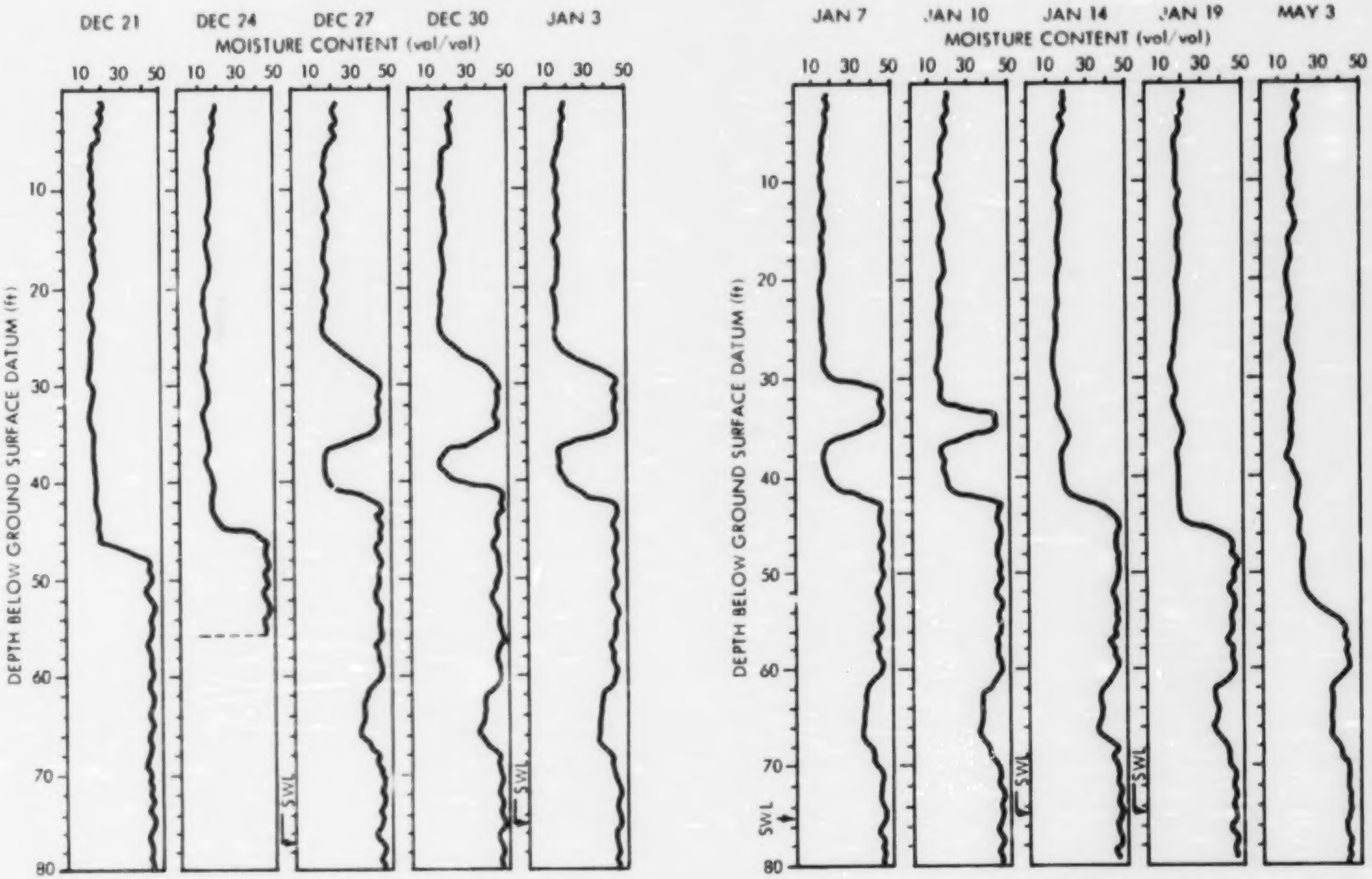

Figure 8. Moisture logs showing growth and dissipation of mounds in the vadose zone (after Wilson and DeCook, 1968).

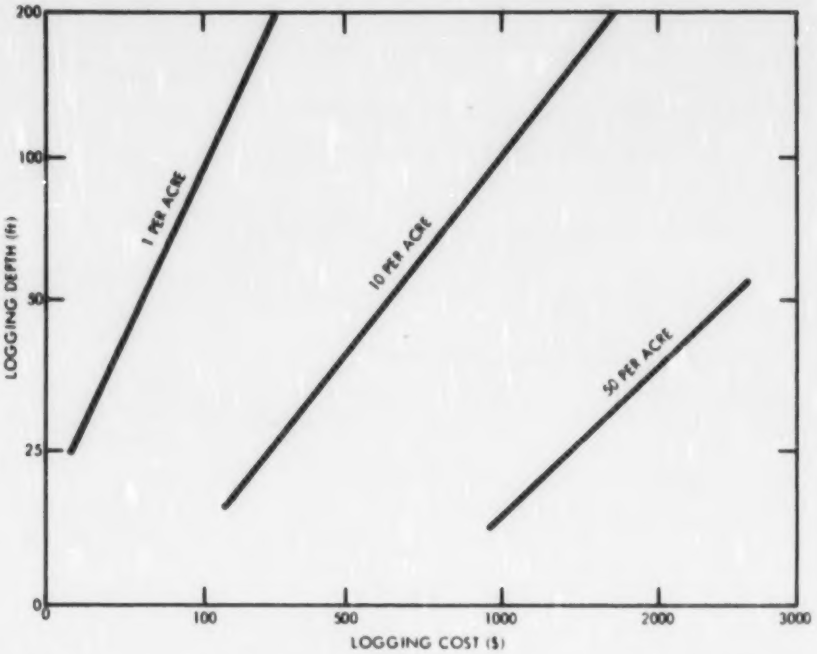

Figure 9. Cost of neutron moisture logging for various depths and sample space densities, December 1974.

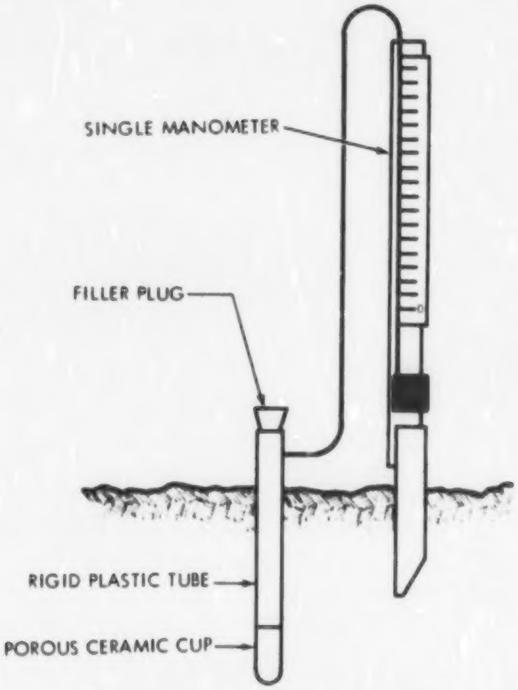
SINGLE MANOMETER
0
FILLER PLUG
RIGID PLASTIC TUBE
POROUS CERAMIC CUP

Figure 10. A single manometer tensiometer.

The cost of a tensiometer including a 6-foot plastic tube is about $30. Figure 11 gives the capital costs of tensiometers placed at various depths and at various sampling densities. The costs presented in Figure 11 do not include installation.

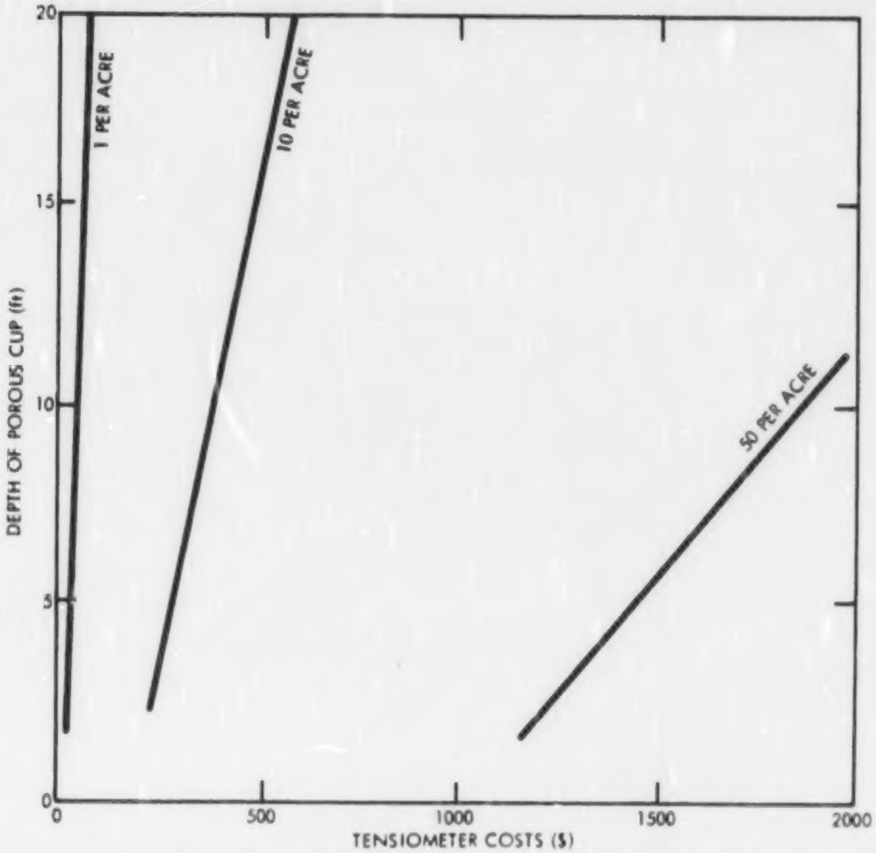

Figure 11. Cost of tensiometers for various depths and sample space densities, December 1974.

Electric Resistance Blocks

Electrical resistance blocks, used to measure either soil-water content or soil-water pressure, consist of electrodes embedded in a suitable porous material such as plaster of paris, fiberglass, or nylon cloth. The principal of operation of these blocks (Holmes et al., 1967) is that water content (or negative pressure) within the blocks responds to the water content (or suction) of the soil with which the blocks are in intimate contact and the electrical resistance properties of the blocks change correspondingly. Moisture blocks are calibrated in soil from the site at which they are to be installed. Such calibration involves evaluating resistance readings against a range of soil-water contents or negative pressures.

Holmes et al. discuss the advantages of resistance blocks, indicating that (1) they appear to be best suited for general use in the study of soil-water relations, (2) they are inexpensive, and (3) they can be calibrated for either suction or water content. Generally, for agricultural applications the blocks are used for negative soil-water pressures greater than 0.8 atmosphere.

The cost of a soil moisture block is about $4. The leads to the soil moisture blocks are very nominal in cost. A soil moisture meter costs about $120. The capital cost, excluding emplacement, of electrical resistance blocks, leads, and a soil moisture meter for various depths and sampling densities is given in Figure 12.

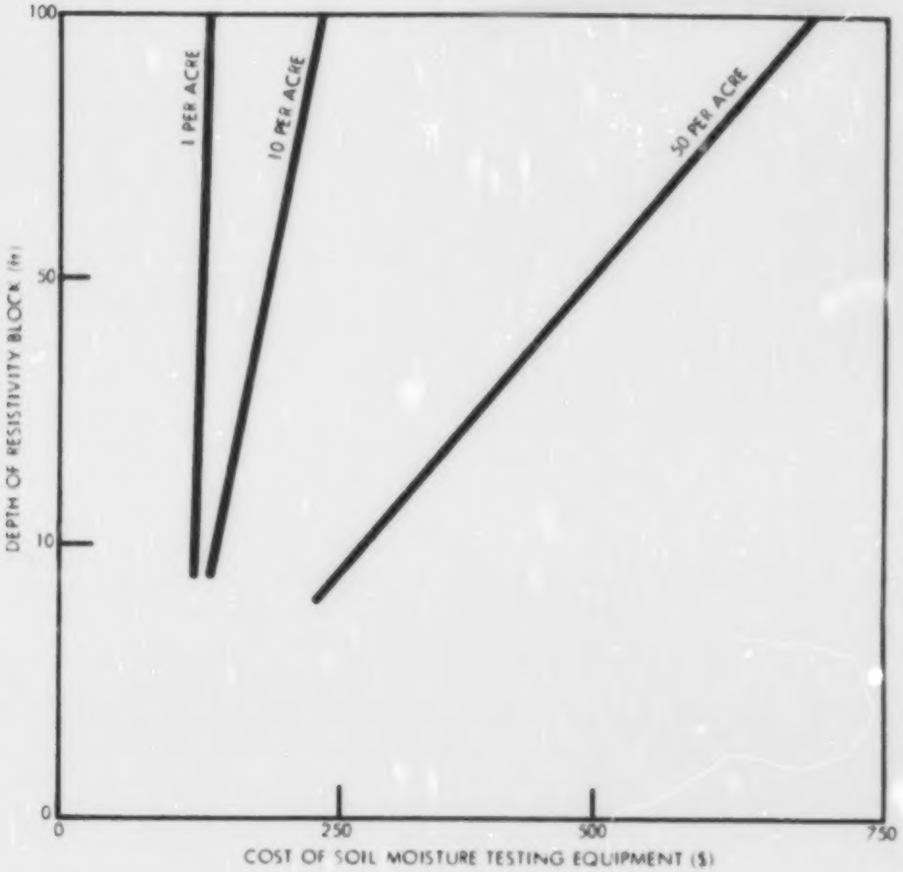

Figure 12. Cost of multiple electrical resistance blocks and soil moisture meter for various depths and sampling densities, December 1974.

Calculation of Water Content

In-situ measurement of water content at some locations, such as beneath waste disposal sites with large areas and relatively deep water tables, may be too cumbersome and expensive to perform. One alternative is to evaluate maximum storage capacity. Porosities for common geologic materials are given in Figure 13. The storage capacity in the vadose zone will be less than that indicated by the porosity because all of the materials are not saturated.

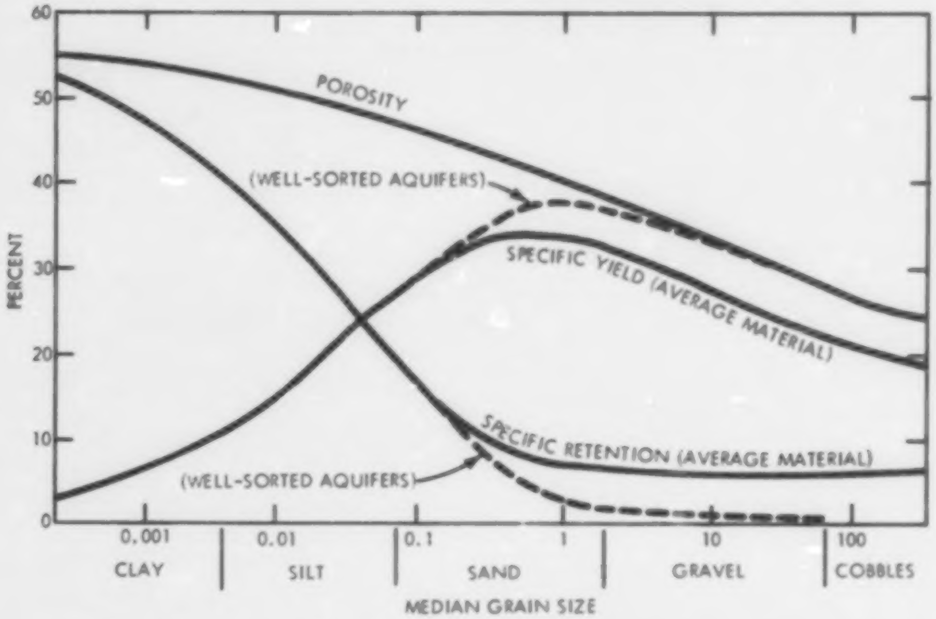

Figure 13. **Relationship between median grain size and water-storage properties of alluvium from large valleys (Davis and DeWiest, 1966).**

Many areas can be divided into two types of vadose zones: those where the specific retention of geologic materials has already been satisfied, and those where it has not. The first case occurs primarily in humid areas where water levels are relatively shallow and an abundant source of recharge has been present for many years. This case also occurs beneath many alluvial basins of the arid west where water tables are within 100 to 200 feet of the land surface and water has been artificially applied at the land surface for decades. The second case is common in arid areas with relatively deep (300 or more feet) water tables. Low natural recharge at the land surface for many years, combined with the presence of soil or subsurface restricting layers, may prohibit natural percolation to the water table. In these cases, the geologic materials may be virtually devoid of water.

The storage capacity for percolated water in cases where the specific retention is satisfied is defined by the specific yield. Representative specific yields for geologic materials are given in Table 5. Where the specific retention has not been satisfied, significant amounts of percolated water will be stored in the vadose zone to make up this deficiency. The total storage capability will then be some value less than the porosity.

TABLE 5. SPECIFIC YIELD VALUES ASSUMED FOR THE SOUTHERN PART OF THE CENTRAL VALLEY, CALIFORNIA (Davis and DeWiest, 1966)

Driller's Description	Assumed Specific Yield %
Gravel, sand and gravel, and similar materials	25
Fine sand, tight sand, tight gravel, and similar materials	10
Clay and gravel, sandy clay, and similar materials	5
Clay and related materials	3
Crystalline rock (fresh)	0

DETERMINATION OF WATER MOVEMENT

An evaluation of water movement above the saturated zone should account for (1) infiltration across the soil surface and movement through the topsoil, (2) movement in perched water tables, and (3) downward movement through the vadose zone. Flux (volume per unit area per unit time) is the principal flow characteristic to be defined in studying water movement in the vadose zone. An important factor in calculating flux is the hydraulic conductivity.

Infiltration Across the Soil Surface

Flux across the soil surface is termed infiltration, the maximum value of which is the infiltration capacity. This characteristic is important in land disposal operations because it indicates the rate at which effluent may percolate to groundwater. Bouwer (1973) categorizes land disposal systems as high-rate or low-rate, reflecting the infiltration rates used to effect effluent treatment.

For existing land disposal operations, effluent can be metered onto each treatment area via suitable flumes, weirs, or flowmeters. Differences in flow rate represent the amount of water which infiltrates on the area. The flux can be calculated (it may be necessary to account for evaporation losses) if the surface area contacted and time that a given volume infiltrated are known.

Movement in Perched Water Tables

Results of neutron logging observations during infiltration tests or examination of data on stratigraphy may indicate the locations of perched water tables in the vadose zone. The principal techniques for monitoring movement in these saturated zones are by the use of piezometers or observation wells.

PIEZOMETERS. Piezometers consist of small-diameter pipes, driven, augered or jetted into a known or expected saturated soil zone. The level of water measured at the base of the piezometer indicates the water level in the saturated zone.

Reeve (1965) discusses in detail the techniques for installing and cleaning new piezometers. In general, it is important to maintain tight contact between the outer wall of the piezometer and the soil. For shallow units, piezometers may be installed by augering and driving with a sledge hammer. Deeper units will require jetting, or use of standard drilling equipment. It may be necessary to fill the cavity between the well and borehole with grout to ensure tightness of fit. As with regular wells, piezometers should be developed by pumping, bailing, etc. to open up material at the base of the unit. In some situations, it may be necessary to install piezometers with screened well points to prevent upward movement of saturated material into the unit.

Depth to water in piezometer units is measured by chalked tape, electric sounders, or air lines. The use and cost of these tools is considered in detail under "Monitoring in the Saturated Zone." By referencing these measurements to a common datum, groundwater levels can be determined for the perched zones. The slope of these elevations indicates the direction of lateral water movement.

Many field soils exhibit anisotropy. That is, the hydraulic conductivity in the horizontal direction may be much greater than in the vertical direction. For such soils it may be advisable to install more than one array or battery of piezometers in a lateral direction away from a recharge source. The bottom openings of piezometers in sequential arrays should terminate at the same elevation. Such an arrangement permits observing lateral head differences resulting from horizontal flow.

The costs of 2- and 4-inch piezometers for various depths and sampling densities are given in Figure 14. The piezometer costs presented do not include installation.

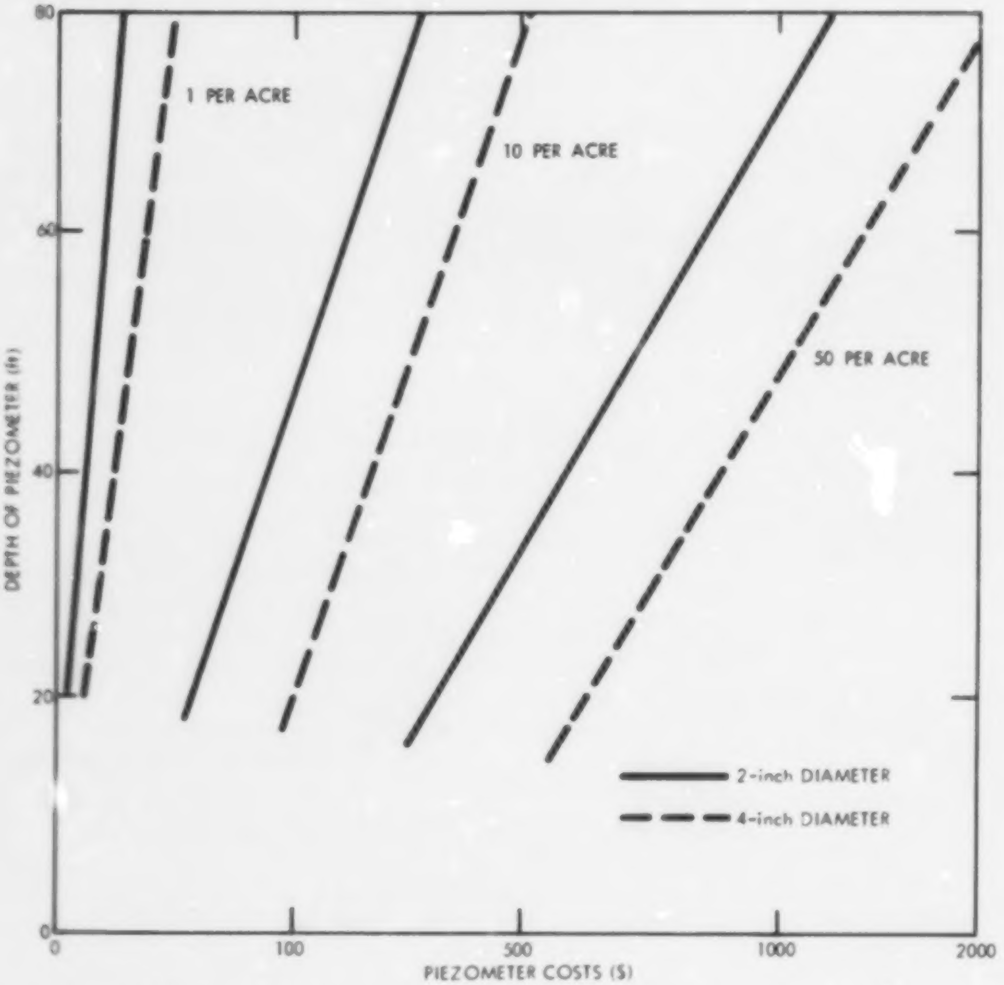

Figure 14. Cost of piezometers for various depths and sampling densities, November 1974.

OBSERVATION WELLS. An observation well consists of an uncased borehole or perforated pipe extending from ground surface into a perched water table. This is similar to a piezometer, except that diameters and depths may be greater.

WATER MOVEMENT IN THE UNSATURATED STATE

Methods for monitoring water movement in saturated regions cannot be used to monitor unsaturated flow because water will not freely enter a soil cavity unless the soil-water pressure is greater than atmospheric. Consequently, special methods must be used in unsaturated soils. Of the available methods the three most commonly used to infer unsaturated flow employ tensiometers, psychrometers, and neutron moisture logging. Several newer techniques, although not extensively field tested, may also have applicability.

Tensiometers

The principles of operation, methods of installation, and limitation of tensiometers are discussed above. In general, tensiometers appear to be the most effective technique for monitoring flow in the soil-water pressure range down to about 0.8 atmosphere (atm). Nielsen et al. (1973) observe that tensiometers are still routinely used and nothing as reliable, accurate, and inexpensive has replaced them in the past 35 years. The application of tensiometers to depths greater than the soil zone is now possible with the advent of pressure transducer units developed by Watson (1967) and others. In characterizing the direction of water movement, a battery of tensiometers must be installed, with units terminating at successive depths throughout the region of interest.

As with piezometers, it is necessary to install more than one array of tensiometers to detect horizontal flow. Thus, if individual arrays terminate at varying depths, differences in total hydraulic heads between corresponding units in successive arrays may suggest lateral movement in the unsaturated state. Because of heterogeneity in soil properties, however, conclusions on lateral flow may not be definitive.

Psychrometers

Tensiometers cannot be used to measure soil-water pressure below about -1 atm because of air-entry problems. To measure lower negative pressures, therefore, other instrumentation is required. In recent years, progress has been made in developing the thermocouple psychrometer for this purpose. According to Watson (1974) in-situ pressure measurements down to -30 atm are possible with these units. The principle of psychrometric measurement of soil-water potential, discussed by Rawlens and Dalton (1967), is that a relationship exists between soil—water potential and the relative humidity of soil water.

Psychrometers consist of a porous bulb comprising a chamber to sample relative humidity of a soil, a sensitive thermocouple, heat sink, reference electrode, and associated electronic circuitry. Two types of thermocouple psychrometers are available. One type, which is installed in access tubes, consists of mounting psychrometers in porous cups at the base of tubing. This unit may be withdrawn for recalibration. The second type, called "sealed-cup" psychrometers by Merrill and Rawlens (1972), contains the thermocouple unit permanently sealed into a porous enclosure.

Each unit must be calibrated prior to field installation—techniques for such calibration are given by Merrill and Rawlens. Also, in field installations it is important to record and correct for diurnal changes in temperature. Installation of a sensitive thermistor is recommended for diurnal studies. Enfield et al. (1973) have used thermocouple psychrometers to estimate the direction and rate of water flux in material above a water table at a depth of 94 meters in a desert environment in Washington. Individual psychrometric units were placed 3 meters apart within a specially designed well casing.

Neutron Moisture Logging

Although the neutron thermalization technique is used mainly to determine changes in volumetric water content of materials in the vadose zone, the method may also be used to infer water movement. In particular, if a soil-water characteristic curve is available for incremental depths throughout the vadose zone, it may be possible to relate water content values to water pressure. Hydraulic head gradients and, therefore, flow directions can then be inferred. Unfortunately, the accuracy of the method may not be great enough to detect slight water content changes, particularly in the dry range. Wilson and DeCook (1968) and Wilson (1971) have used moisture logs from a network of 30-meter deep access wells to infer the rates of lateral movement of recharge waves in the vadose zone during river recharge and artificial recharge. The arrival of such waves was inferred by the change in water content in a perched mound at about 10 meters.

Moisture Blocks

Moisture blocks of the type described earlier may be used to measure soil-water pressure if suitable soil-water characteristic curves are available. A unit relying on the sensing of heat dissipation within the block (Phene et al., 1971) may have future promise.

Quantification of Flux in Unsaturated Media

Two of the physical characteristics of interest in the vadose zone are soil-water flux and hydraulic conductivity. Under continuous flooding at waste disposal facilities, the steady-state value of infiltration approaches the saturated hydraulic conductivity. Presumably, the steady-state value of flux below the soil surface also approaches this value; therefore an approximation of the flux value in the wetted soil profile can be obtained during a wetting cycle.

Of equal interest is the flux during drying periods. Three major approaches to evaluating flux in the vadose zone during a drying cycle are: (1) measuring water content changes in profiles as a function of time; (2) using appropriate mathematical expressions and empirically determined relationships between soil-water pressure, soil-water content, and hydraulic conductivity; and (3) direct measurements using flowmeters.

RELATING WATER CONTENT CHANGES TO FLUX. The difference in water content stored in a wetted profile between successive time measurements above a certain depth is a measure of the amount of water which has flowed out of that depth. The water content versus depth curves may have been obtained from tensiometer data, moisture logs, etc. This relationship assumes that the water in storage from the surface to the first tensiometer equals the value at the first tensiometer times the thickness of materials above this point.

EXPRESSIONS FOR FLUX AND HYDRAULIC CONDUCTIVITY. Field plots instrumented with tensiometers are required to determine flux and hydraulic conductivity (Nielsen et al., 1973). Infiltration is allowed to progress in each plot to the point that steady-state values are reached. After recession of the water surface, the soil surface is covered to prevent evaporation. When drainage has occurred to the point that the hydraulic gradient becomes unity, tensiometer readings are taken in incremental time steps from successive tensiometer units. At the completion of the study, intact cores of soil are taken in increments throughout the profile. Such samples are used for the laboratory determination of soil-water characteristic curves. Subsequently, the soil-water pressure data taken by tensiometers during the field study are translated to equivalent water content values. Spatial variations occur in the soil properties; consequently, a sufficient number of field plots are needed to provide a measure of this variability. Furthermore, even though the assumption of unit hydraulic gradient is fulfilled, problems may arise if subsurface heterogeneities affect flow. Problems of anisotropy and stratification will be accentuated with depth in the vadose zone. Realistically, it may be expected that flux expressions are most useful in the soil zone.

DIRECT MEASUREMENT OF FLUX. Attempts have been made in recent years to develop equipment to measure soil-water flux in the unsaturated state which do not require information on the hydraulic conductivity.

Two types of flowmeters reported by Cary (1973) involve (1) direct flow measurement, and (2) the displacement of a thermal field by water in motion. The direct flow unit measures the flow of soil water intercepted by a porous tube containing a sensitive flow transducer. The second unit measures very accurately the transfer of a heat pulse in water moving within a porous cup buried in the soil. Because of the intimate contact between the soil and porous cup, the water moving in the cup forms a continuum with soil water. Laboratory calibration curves are prepared to relate the output of a sensitive millivolt recorder, during imposition of heat pulses, to empirically measured flow rates.

For field installation, porous discs containing either flow transducers or heat sources are mounted in cylinders which are buried in the soil. A limitation, therefore, is that flow is measured in disturbed soils. To date, no data are available on the use of such flowmeters in deep vadose zones.

Calculation of Approximate Flow Rates

Vertical flow in the vadose zone is related to the infiltration rate of waters applied at the land surface, storage capacity of the vadose zone, and depth to the water table. If the water table remains at a relatively constant depth and a specific amount of water percolates from the topsoil, then the flow rate of water in the vadose zone is partly controlled by the available storage space therein. With point or line sources, significant lateral movement can occur in layered deposits above the water table; however, for diffuse sources of large areal extent, such as agricultural return flow, these lateral movements may be neglected.

For example, assume that 25 feet of water is applied per acre per year at the land surface and 20 feet percolate from the topsoil. Assume the depth to water is 55 feet and the vadose zone beneath the topsoil is 50 feet thick. Assuming that the porosity is 30 percent and the specific yield is 15 percent, and that the specific retention has already been satisfied, then the storage capacity in the zone is a maximum of 50 times 0.15, or 7.5 feet. It is clear that the vadose zone could hold this water for only a few months at the most.

As a second example, assume that 5 feet of water is applied per acre per year at the land surface and 2 feet percolate from the topsoil. Assume the depth to the water table is 310 feet and the vadose zone is 300 feet thick. Assume that the porosity is 40 percent and the specific retention is 15 percent but that the moisture content is only 5 percent. Thus, the storage capacity in the zone is a maximum of 300 feet times 0.10 or 30 feet of water. As a result it would require 15 years for the percolating water to satisfy storage before reaching the water table.

Use of Tracers

Tracers such as salts, dyes, and radioisotopes can be employed to measure flow rates in the vadose zone. Care must be taken to insure that the tracer moves at the same velocity as the water (which, however, is not necessarily the velocity of a specific groundwater pollutant). The practical problem of detecting or sampling a tracer at increasing depths under unsaturated conditions should not be minimized. Smith (1974) reports on using tritium as a tracer in the unsaturated zone.

WATER SAMPLING IN THE VADOSE ZONE

In a program to monitor quality in the vadose zone samples may be needed from both unsaturated and saturated (perched water table) regions.

Sampling in Saturated Regions

WELLS AND PIEZOMETERS. Preliminary hydrogeological surveys will often delineate existing or potential perched water table regions. Many of these regions may be instrumented with wells or piezometers which can be modified or used directly for sampling water quality. In general, observation wells are unperforated throughout the vadose zone to prevent cascading water from perched layers affecting water level measurements and water quality at the water table. It may be possible, however, to modify such wells for sampling without causing cascading. For example, the results of neutron logging in a well may reflect the presence of perched layers. It is possible to perforate the casing of abandoned wells at these depth intervals and install packer assemblies to isolate these regions for sampling and prevent cascading. Alternatively, if information on the location of perched layers is known prior to the construction of a new well, the well can be designed to permit sampling of these regions.

An array of piezometers can be used for water sampling in perched zones. If the locations of such zones are known, individual units can be designed with screened well points. If units in the individual arrays terminate at varying depths, samples from such an array will indicate vertical quality changes from movement of effluent. Similarly, if a number of arrays are distributed in a horizontal transect, samples from individual units terminating at the same elevation will manifest quality changes from lateral spread of effluent.

For programs to monitor the spread of heavy metals in effluent water it is necessary to construct wells or piezometers from materials which will not contribute metals to the sample. Wells cased with PVC pipe will avoid this problem, particularly if screens are also of plastic, but require special construction techniques.

To obtain water samples from wells it is necessary to employ some type of sampling device. A simple bailer may often be used with success. This unit consists of a tube with an open top and a ball check-valve at the bottom to admit water samples.

Another commonly used sampler consists of a sampling tube or body with an air inlet line and a sample outflow line extending to the surface. The lower end of the body contains a spring-loaded flap valve. The sampling line extends to the base of the sampler and the air inlet line terminates a slight distance below the top. In operation, the sampler is lowered into a well to the sampling depth below the water table. After permitting the sampler to fill, air pressure is applied to the air line and the sample is forced to the surface through the sampler line. Advantages of this unit are that it need not be removed from the well between samples. Also, samples are obtainable at various depths below the water table. A disadvantage is that air is introduced into the sample, possibly interfering with certain chemical determinations. This possibility can be avoided by using compressed nitrogen gas.

Allison (1971) discusses a simple device for sampling water in auger holes, which also could be used in cased wells. Basically, the unit consists of plastic tubing of sufficient length to extend into the water table. The upper end of the tube terminates in a collector flask. A second line from the flask is connected to a hand-held vacuum pump. When the pump evacuates the flask and tubing, water is forced up into the flask. According to Allison such a system is capable of sampling water to a depth of 7.4 meters.

In addition to these samplers several other types are available, including positive displacement pumps. Some operations may warrant the purchase of a small-diameter submersible pump mounted on a flexible line.

With any sampling method it is important to ensure that an uncontaminated sample is obtained. The well should be bailed or pumped extensively at the beginning of each collection period to ensure the movement of fresh groundwater into the well. Similarly, the bailer or sampling lines should be flushed out several times before a sample is collected.

SAMPLING TILE DRAIN OUTFLOW. If a tile drainage system has been installed to promote rapid drainage of a perched water table, samples can be collected from the tile outfall. In some cases it may be desirable to install commercially available composite or discrete sampling devices.

Willardson et al. (1973) discuss a "flow-path ground water sampler," which enables collection of water in different flow paths around a tile.

FIBERGLASS PROBES. Hansen and Harris (1974) describe a sampler capable of discrete simultaneous sampling at several depths below a water table. The unit consists of a series of isolated fiberglass probes in a wellpoint, with individual lines from each probe running to the surface. Each isolated area is filled with a sand matrix. During collection, all probes are sampled simultaneously, via a vacuum pump, to minimize interference with natural flow within the sampling region.

LYSIMETERS OR SAMPLING CHAMBERS. In the context of this discussion, a lysimeter, or sampling chamber, consists of a trench or large-diameter culvert sunk vertically into a waste disposal area. Lysimeters are installed to permit sampling of the soil solution throughout a vertical profile, usually several meters in thickness. Culvert type lysimeters were used by McMichael and McKee (1966) in their studies on wastewater reclamation at Whittier Narrows. Parizek and Lane (1970) used trench lysimeters to collect samples from forest soil during effluent irrigation in Pennsylvania.

The lysimeters developed by McMichael and McKee (1966) employed pan samplers for the collection of water during periods of saturation in a profile to a depth of about 3 meters. These samplers were conical in shape, 61 cm in diameter and 23 cm deep. The samplers were installed at various depths at a radial distance of about 3 meters from the central well. Individual sampling pans were filled with gravel to prevent clogging, and each was connected to the central culvert via tubing. Excavations used for installation of the samplers were carefully backfilled. During sampling, percolate intercepted by the pans flowed by gravity to the central well and into collection flasks.

The trench lysimeter described by Parizek and Lane (1970) also used pan samplers. The largest such lysimeter consisted of a 1.2-meter wide, 4-meter long trench excavated to a depth of about 6 meters. The sides of the trench were braced and lined with wood. Sampling pans were installed at 30-cm vertical intervals to the 6-meter depth of the lysimeter. The pans, constructed from galvanized metal, were 30 cm by 45 cm with copper tubing to permit sample drainage. Each unit was sunk into the soil a short distance from the side walls of the lysimeter. During application of effluent, samples of percolate intercepted by the pans were collected in flasks within the lysimeter.

A basic problem with collection pans, pointed out by Parizek and Lane (1970) is that samples are collected only when the soil-water pressure is greater than atmospheric. Consequently, after cessation of infiltration the soil-water system may shift rapidly to the unsaturated state, prohibiting sample collection. The same problem exists for piezometers, auger holes, or other sampling methods requiring saturation.

Sampling in Unsaturated Regions

SOIL SAMPLING. One method for determining the quality of the soil solution in unsaturated soils is to obtain field samples from which saturated extracts can be obtained. An extensive program of soil sampling throughout the duration of a waste disposal operation could be prohibitively expensive, however, particularly if samples were required from the entire vadose zone.

SUCTION CUPS. An alternative to soil sampling for characterization of the water quality of unsaturated soils is to utilize ceramic cups like those used in tensiometers. When placed in the soil, the pores in these cups become an extension of the pore space of the soil so that the soil-water content in the soil and cup become equilibrated at the existing soil-water pressure.

Applying a slight vacuum to the interior of the cup causes the soil solution to flow into the cup. The quality of the soil solution can be determined by bringing this sample to the surface. Although ceramic cups have limitations, at the present time they appear to be the best tool available for sampling unsaturated media.

The basic design of the sampling unit is as follows: a ceramic cup is sealed onto a rigid-plastic body tube that is equal in length to the desired sampling depth. Small-diameter tubing is inserted through a rubber stopper, which seals the top of the body tube, down to the inside base of the cup. The other end of the tubing is attached to a collection flask through a two-hole rubber stopper. Vacuum is applied to a second line in the flask causing the air pressure inside the system to become less than the ambient pressure at the cup's location. Soil solution is drawn into the cup and sucked through the vacuum line to the collection flask. The technique used to emplace suction cups is the same as that for tensiometers. In particular, good contact should be obtained between the cup and the soil.

Recently, alternative designs have been reported in the literature, most notably by Parizek and Lane (1970) and by Wood (1973), that allow raising samples from greater depths than is possible by vacuum withdrawal. The design used by Parizek and Lane is shown schematically in Figure 15. The body tube of the sampling unit is 2 feet long and holds about a liter of sample. Two copper lines are forced through a two-hole rubber stopper which seals the body tube. One line, the sample discharge line, extends to the base of the ceramic cup, as shown, and the other, a pressure-vacuum line, terminates a short distance below the rubber stopper. The discharge line connects to a suitable vacuum-pressure pump. In operation, a vacuum is applied to the system with the discharge tube clamped shut. When sufficient time has elapsed for the unit to fill with soil solution, the vacuum is released, the clamp on the outlet line is opened, and air pressure is applied to the system to force the sample into the collection flask.

Figure 15 also illustrates another feature of the design of Parizek and Lane. The installation method shown does not require an intimate contact between the cup and the soil. Instead, a cavity larger than the cup is drilled to permit backfilling with silica sand around the cup and with tamped backfill for the remainder of the length. This design permits the installation of more than one unit in a hole, although three is about the maximum. Each unit is sealed from adjoining units with bentonite. According to the authors the silica sand provides a clean medium for soil moisture moving toward the cup, ensures contact between soil and cup, eliminates unevenness in the void space, and precludes clogging of the cup by colloidal material. Samples were recovered from a depth of 15 meters; 17 meters is about the maximum expected recovery depth with this basic design.

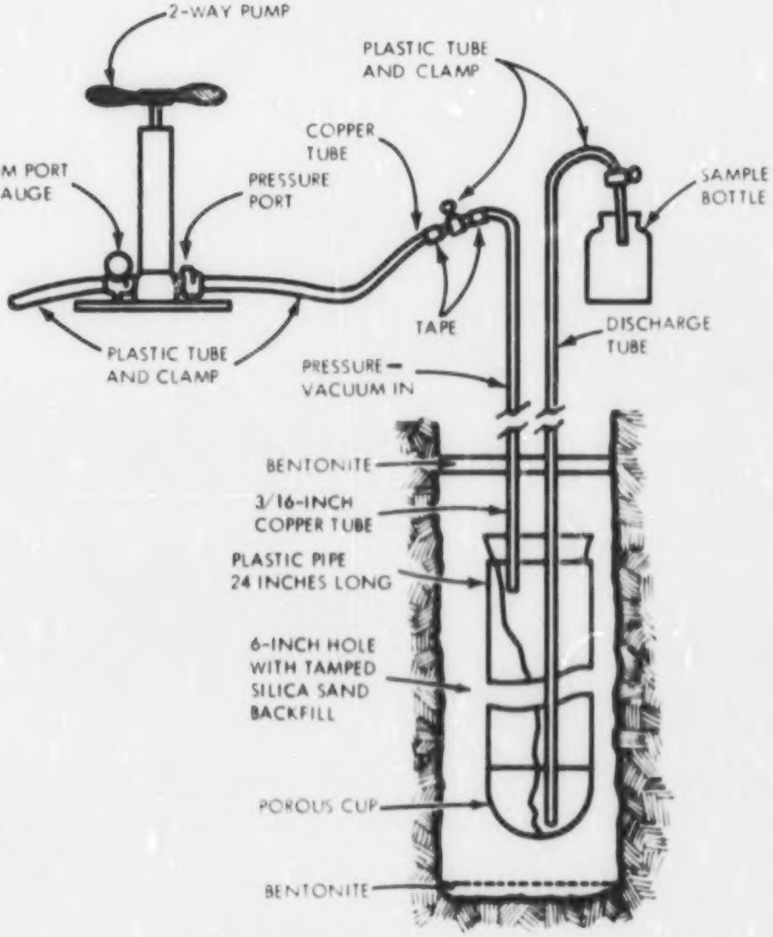
2-WAY PUMP
PLASTIC TUBE AND CLAMP
COPPER TUBE
VACUUM PORT AND GAUGE
PRESSURE PORT
SAMPLE BOTTLE
TAPE
DISCHARGE TUBE
PLASTIC TUBE AND CLAMP
PRESSURE— VACUUM IN
BENTONITE
3/16-INCH COPPER TUBE
PLASTIC PIPE 24 INCHES LONG
6-INCH HOLE WITH TAMPED SILICA SAND BACKFILL
POROUS CUP
BENTONITE

Figure 15. Cross section of suction cup assembly and backfilling material (after Parizek and Lane, 1970).

Wood (1973) reports on a modified version of the design of Parizek and Lane that overcomes a basic problem with their system, i.e., solution being forced back into the soil during the release of vacuum and application of pressure. A sketch of Wood's design is shown in Figure 16; details are presented in his paper. The important feature, however, is that a check-valve is included in the pressure-delivery tube assembly within the cup. In operation, vacuum is applied to the system, inducing a flow of water into the cup and tube assembly. Nitrogen gas pressure is applied to one tube and the sample is forced to the surface. The check-valve prohibits pressurization of the porous cup and, therefore, a sample within the cup does not flow back into the soil.

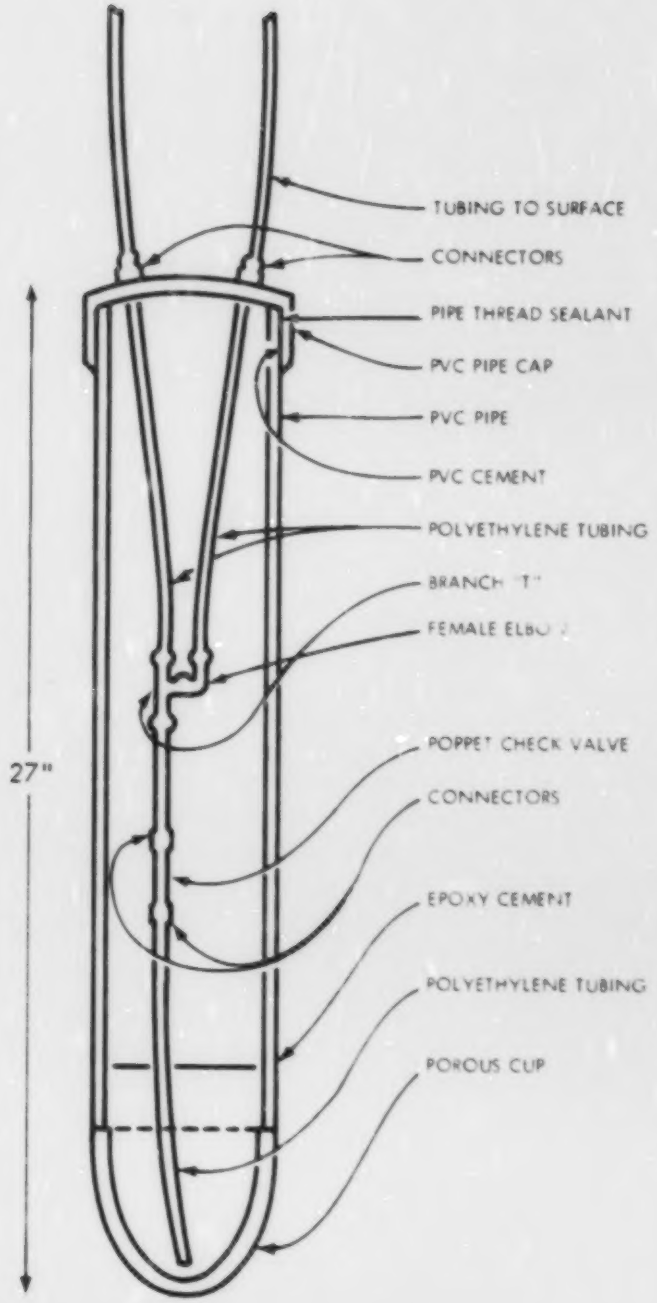
TUBING TO SURFACE
CONNECTORS
PIPE THREAD SEALANT
PVC PIPE CAP
PVC PIPE
PVC CEMENT
POLYETHYLENE TUBING
BRANCH "T"
FEMALE ELBOW
POPPET CHECK VALVE
CONNECTORS
EPOXY CEMENT
POLYETHYLENE TUBING
POROUS CUP
27"

Figure 16. Cross section of porous cup assembly with pressure control (after Wood, 1973).

Wood's installation procedure consisted of drilling a 10-cm hole with a continuous flight auger to 45 cm from the desired depth. The auger was then installed in the lowermost auger flight and the ensemble pressed back into the hole to the final depth. The assembly was again withdrawn and a suction cup unit was placed into the hole. Only one unit was installed per hole; samples were collected from depths ranging to 36 meters.

Although suction cup assemblies are the best available techniques for obtaining samples of the soil solution in situ, certain problems accompany their usage. One is that samples cannot be obtained over the entire range of soil-water pressures: suction cups are capable of sampling only at pressures greater than about -1.0 atmosphere. Because of the very small pores in ceramic cups, inflow of suspended solids is inhibited, making tests for biochemical oxygen demand (BOD) on collected samples inaccurate. Similarly, bacteria may be filtered out. During application of vacuum to the cups, it is important that the negative pressure closely match the pressure of the soil-water system. If the vacuum differential is excessive, the additional suction can influence the movement of soil water in the vicinity of the cup.

SALINITY SENSORS. A recent development for in-situ evaluation of soil salinity is the so-called "salinity sensor." The basis of these devices is the relationship between specific electrical conductance (EC) of soil solution and the total concentration of salts in solution.

The salinity sensor described by Richards (1966) uses electrodes embedded in porous ceramic to form a hydraulic continuum with soil water and measure the specific conductance of the soil solution directly. EC values can then be directly related to the total salt content by suitable calibration relations. The unit described by Richards comprises a plate about 1 mm thick with platinum electrodes fixed in place on opposing faces. An interesting feature of the sensor is that the unit is spring loaded to ensure good contact with soil. Because of the strong dependency of EC on temperature, it is important to measure accurately the temperature of the soil solution. Richards used a thermistor to provide temperature compensation.

Oster and Willardson (1971) have reviewed problems arising from calibration and field use of salinity sensors. Of particular importance is their observation that sensors should not be used at soil-water pressures less than -2 atmospheres. Also they indicate that when sensors are placed in trenches at field sites, the permeability of the materials in the back-filled trench tends to be greater than in indigenous soil. During leaching trials, therefore, the salinity measured with the sensors tended to be lower than in adjacent soil. Differences were attributed to greater leaching in the trench, probably because pore sizes in the trench soil were of a different range than indigeneous soil.

While salinity sensors may be useful to gage changes in the total salinity of a soil solution, in waste disposal operations, concentrations of individual constituents may be of more importance. Furthermore, the water pressure of materials in the lower reaches of the vadose zone may be less than -2 atmospheres, thereby rendering the unit inoperative.

The cost of a salinity bridge is about $620. Each salinity sensor costs about $35. Sensor cable costs about $0.50 per foot. Figure 17 gives the cost for a salinity bridge and various depths and sampling densities for the sensors.

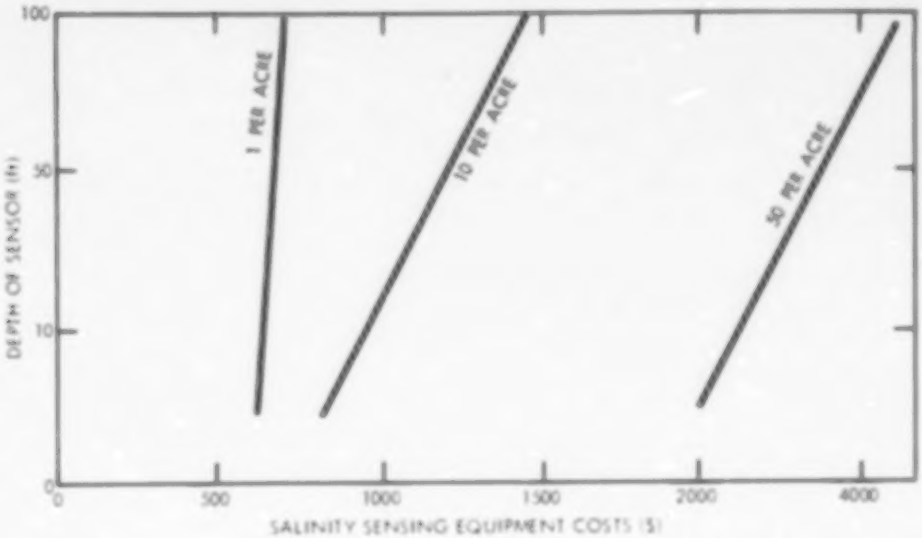

Figure 17. Cost of soil salinity sensors and a salinity bridge for various depths and sampling densities, November 1974.

SECTION IV

MONITORING IN THE ZONE OF SATURATION

INTRODUCTION

Differences in the mineral composition of rocks within the groundwater reservoir, in the composition of soils, and in the chemical composition of recharge waters, cause differences in groundwater quality from place to place. Selection of a sampling site and collection of groundwater quality data is more difficult than for surface water. This is due to the complexity and accessibility of most aquifer systems and the multitude of factors which influence groundwater quality (Brown et al., 1970). The superposition of pollution zones on the natural system imparts an additional degree of complexity.

Knowledge of the hydrogeologic framework is important from two standpoints: (1) prediction of groundwater movement, and (2) geochemical considerations which affect natural groundwater quality. The three-dimensional distribution of hydraulic head and geologic conditions largely determines groundwater flow patterns. The pattern of movement of groundwater has a major effect on the distribution of groundwater pollutants. Both regional and local conditions are significant. Sources of pollution must be identified, and volumes and quality of wastewater or percolate determined. The three-dimensional distribution of groundwater quality must be delineated.

Methods employed in general groundwater studies are summarized in this section, followed by details of specific methods of monitoring pollution in the saturated zone. These methods illustrate some of the data required for groundwater pollution monitoring.

GENERAL MONITORING PROCEDURES

Development of the hydrogeologic framework entails surface phenomena (such as precipitation and streamflow), interactions in the topsoil and unsaturated zone, and considerations of the saturated zone and well hydraulics. In this section the saturated zone is of prime consideration. Brown et al. (1972) have summarized international data on groundwater studies. The U.S. Geological Survey has issued periodic reports under Techniques of Water Resources Investigations. Textbooks on groundwater contain abundant information on the subject, including Todd (1959) and Davis and DeWiest (1966). Walton (1970) presented case histories of groundwater studies, while issues of Ground Water and other periodicals contain numerous reports on groundwater.

Well Inventory and Well Data Collection

Most groundwater studies require a complete field well inventory and office compilation of existing well data. Data such as driller's logs, electric logs, water-level measurements, pump tests, and chemical analyses are gathered and organized. Field observations and interviews are used to verify the correspondence between data and wells. Considerable confusion can result when this process is not carefully done. It also promotes the proper interpretation of results of a monitoring program. The cooperation and assistance of local water agencies is necessary for successful accomplishment of this initial work.

Geological Framework

The geological framework for groundwater studies includes lithology, texture, structure, mineralogy, and the distribution of the subsurface materials through which groundwater flows. The hydraulic properties of earth materials depend on their origin and lithology, as well as the subsequent stresses to which the rocks have been subjected. Weathering, tectonic movement, and fracturing are examples of these stresses.

Surface geology is commonly mapped in the field if sufficiently detailed reports or maps are not available. Photogeology is a useful tool in analysis of surface or near-surface geologic conditions. Ray (1960) and Seker (1966) discuss the use of aerial photographs in geologic interpretation and mapping and applications to groundwater. Geologic maps are compiled to indicate the distribution of rock types and structural features such as folds or faults. Geophysical methods can provide information about the major features of the underground materials. Zohdy et al. (1974) summarize the application of surface geophysics to groundwater investigations. Geophysics can also provide a good indication of where test drilling should be undertaken to ascertain more information on the configuration of the subsurface materials.

Records of geologic materials penetrated during well drilling are extremely important. Driller's and geologist's logs can often be correlated with borehole geophysics. Keys and MacCary (1971) summarize the application of borehole geophysics to water-resources investigations. The vertical distribution and occurrence of subsurface materials are thus documented at the point where a well is drilled. Electrical resistivity and spontaneous potential logs (electric logs) provide information on the subsurface lithology. A gamma-ray log indicates clay content in sedimentary rocks. This method is used in cased holes, and can be quite effective in alluvial materials (alternating layers of sand and clay).

Once data on subsurface geology are compiled, cross sections are developed on the basis of geological correlation. The three-dimensional variations in the subsurface lithology are thus illustrated. Considerations of importance in water quality studies include chemical composition on the underground materials and contained fluids.

Water Levels and Groundwater Movement

Groundwater movement depends on the permeability and the hydraulic gradient within an aquifer. Permeability is related to the nature, size, and degree of interconnection of pores, fissures, joints, and other openings. Water-level measurements are used to draw contours of depth to water and groundwater level elevation over the area of interest. Similarly, water-level measurements at different depths in the aquifer can provide an indication of the vertical flow components. Schematic flow nets are made to illustrate the movement of groundwater in the aquifer (Casagrande, 1937; Davis and DeWiest, 1966). Flow nets provide information on recharge to and discharge from the aquifer, relative direction of groundwater movement, and aquifer geometry and permeability.

Flow lines are perpendicular to water-level elevation contours only in the case of homogeneous and isotropic media. The subsurface lithology is used to evaluate locations where the direction of movement of groundwater may not be perpendicular to these contours, such as in buried stream channels in alluvium. Water-level contours are generally drawn for static conditions, and pumping wells may alter the dynamic situation.

Groundwater velocities can be estimated on the basis of permeability or transmissivity, hydraulic gradient, and porosity. Permeability and transmissivity are commonly determined from analyses of pumping tests. The hydraulic gradient is determined from the water-level contour map, and porosities are known or can be determined for most materials. In the case of confined aquifers and relatively impermeable confining beds, vertical permeability and hydraulic gradients can be used to calculate upward or downward leakage. Similarly, amounts of groundwater flowing through an area can be calculated based upon permeability or transmissivity and the hydraulic gradient. Tracers such as dyes (UNESCO, 1975) or radionuclides (Havely and Nir, 1962; Hanshaw et al., 1965; Kaufman and Orlob, 1956) can also be used as an indication of groundwater flow velocity.

Pump Tests and Aquifer Analysis

The hydraulic properties of aquifers are determined using pumping or recharge tests, and water-level changes reflecting long-term conditions at the aquifer boundaries. The first method is widely used because it may permit evaluation of the aquifer parameters in a relatively short period of time. Theis (1935), Jacob (1947), Ferris et al. (1962), Johnson Division UOP (1966), Todd (1959), Davis and DeWiest (1966), and Walton (1970) summarize methods of pump testing and aquifer analysis.

The primary aquifer parameters determined from most pump tests are transmissivity and storage coefficient. They are used to define groundwater movement and the reactions of aquifers to pumping or recharge. Permeability can also be determined, which helps indicate flow velocities. Calculation of groundwater flow through certain sections of the aquifer are valuable in order to assess spread and dilution of pollutants from the land surface.

Much of the theory and equations developed for aquifer analysis apply to confined aquifers in porous, granular, unconsolidated materials. Special equations have been developed for unconfined aquifers, leaky aquifers, and aquifers of very irregular geometry. Jointed, fissured, and cavernous rocks are characterized by a high degree of heterogeneity. In rocks with secondary porosity and permeability developed by jointing or solution, single pump tests of short duration seldom provide any information except localized aquifer characteristics.

By considering a large area, variations and heterogeneity of local areas tend to average out and usable figures on the hydraulic characteristics may be obtained. If continuing records of recharge to and discharge from sizable parts of the aquifer are available, along with records of seasonal fluctuations of the water table, then reliable estimates of the regional hydrologic characteristics can be made.

Water Budget and Modeling

The law of conservation of matter defines the groundwater basin water budget. All water entering a specific area must go into storage within its boundaries, be consumed therein, be exported therefrom, or flow out as surface or groundwater.

Water budgets can be used to indicate regional conditions in an aquifer. The reaction of the aquifer to pumping or recharge can be determined by comparing the water budget with water-level hydrographs. Water budget analysis can also serve as an independent check on the accuracy of individual items in the budget. Mathematical and analog modeling, along with computer methods, are important tools in analyses of regional groundwater systems (Skibitzke, 1960; Stallman, 1963; Walton and Prickett, 1963). Projections of future changes in aquifer regime can be made based on these model studies.

The groundwater regime is greatly influenced by climatic, hydrologic, biologic, and soil factors. Groundwater is closely interrelated with surface water and soil moisture. The groundwater budget requires quantification of all these factors affecting inflow to, and outflow from, a groundwater reservoir, as well as storage changes. Few of the factors are directly measurable, but some can be determined by residuals of measured variables and others can be reasonably estimated. Of foremost importance is the proper selection of groundwater basin boundaries based on hydrogeologic factors.

Water Temperature and Chemical Quality

Temperature of underground materials is influenced by the heat input and output, as well as by the heat characteristics of the materials. Since the rock and water below the land surface are poor conductors, the temperature distribution is influenced by groundwater movement. Groundwater temperature is an important field of study. Well discharge and down-hole water temperature measurements can indicate directions of water movement and relative permeabilities of aquifer materials. Groundwater temperature affects the chemical quality of groundwater. Groundwater temperatures can be used as an independent check on concepts based on hydraulic and geologic reasoning alone. Bredehoeft and Papadopulos (1965), Cartwright (1968), Sammel (1968), and Bentall (1963) discuss the significance of temperature measurements in groundwater.

Groundwater quality studies also provide an independent check on concepts based on physical reasoning alone. A groundwater quality study is based on a knowledge of the geochemistry of aquifer materials and the chemistry of recharge to the aquifer. Chemical equilibrium and kinetics evaluations may indicate whether certain minerals are dissolving, or precipitating, as well as rates of reactions. Hem (1970) has reviewed pertinent data on natural water quality. Changes in groundwater quality during flow through the aquifer can be assessed. The relative mobility of certain chemical species and of biological and radiological parameters is of great concern. Some constituents may move through the aquifer at the same rate as the water, many move at slower rates, and some are virtually immobile.

Contours for constituent concentrations on an areal and vertical basis are often prepared. These can be compared with geologic maps, flow nets, and predominant sources at the land surface. Quite often several constituents such as sodium and chloride, or calcium and sulfate, are interrelated because of the subsurface presence of solid compounds. Subsurface lithology and temperature may correlate well with groundwater quality. Numerous graphical procedures are available for interpretative work. The trilinear diagram is a useful tool to compare water types. The major cations (Ca, Mg, Na + K) are plotted on one triangle and the major anions (Cl, SO_4, $HCO_3 + CO_3$) are plotted on another. This tool is especially helpful in analyzing mixtures of two or more types of groundwater.

SPECIFIC MONITORING METHODS

Surface Geophysics

Often, a major part of an investigation of groundwater pollution is to locate and define its extent. In special situations a resistivity survey can be effectively used. These situations generally occur where:

1. There are either no wells or only a few in the polluted zone
2. The polluted water is of relatively high salinity compared to native groundwater in the area
3. The subsurface geology is relatively well understood
4. The water table is fairly shallow.

Griffiths and King (1969) summarize the resistivity method and common applications. Zohdy et al. (1974) summarize the application of surface geophysics to groundwater investigations.

Earth materials containing groundwater of high electrical conductivity will have lower resistivity values than surrounding materials containing natural groundwater. In some cases, the resistivity method can be used to determine quickly the boundaries of the zone of polluted groundwater. Hackbarth (1971) describes the use of resistivity measurements to analyze spent sulfite liquor recharge movement. Merkel (1972) illustrates how resistivity surveys could be used to analyze acid mine drainage in groundwater. Stollar and Roux (1975) summarize the use of resistivity surveys to define groundwater pollution.

Initially, multidepth electrical soundings are made of the area in an attempt to see if the top and bottom of the polluted zone can be delineated. If this can be done, a series of single-depth resistivity measurements are then made at selected points to define the horizontal extent of the plume. By varying the depth of the measurements within the vertical extent of the plume, the three-dimensional extent of the polluted zone can be determined.

The resistivity survey has certain limitations that restrict wide application. These include poor site access, interference of conductors such as pipelines, insufficient contrast between the conductivity of the polluted and the natural groundwater, depth to the top of the polluted zone, thickness of the zone, and the complexity of the surficial geology (Stollar and Roux, 1975). An inherent problem in any resistivity survey which incorporates an electrode configuration consisting of all surface electrodes is that of resolution when the lithology has high resistivity contrasts. A highly resistive zone inhibits current flow in it or reaching regions below it. Similarly, a highly conducting zone traps the current and again allows little current to flow below it. For examinations at considerable depths, a technique has been developed which incorporates the use of a buried current source in a drill hole.

The primary advantage of the resistivity method in groundwater pollution investigations is to provide information on the extent of the polluted zone at a reduced cost and within a short period of time. Hackbarth (1971) states that resistivity measurements can be useful in supplementing data obtained from piezometers, but cannot replace them.

In conducting a resistivity survey the variables of concern are the depth to the top of the plume, the thickness of the polluted zone, and the areal extent of the polluted zone. If no data are available a feasibility study can be done for about $1500 to determine whether the technique will work and to estimate the plume size. If the survey appears feasible, the cost that will be incurred by an experienced geophysical team can be estimated from Table 6.

The first step in the survey is to determine the electrode spread. The spread will depend upon the depth of the plume and its thickness. Both of these variables may not be known but they can be estimated and used in Table 6(a) to determine the electrode spacing. The areal extent of the plume must be estimated in acres and applied in Table 6(b) to determine the number of surveys to be conducted. From Table 6(c) the time required to conduct each study for a particular plume depth, thickness, and areal coverage can be obtained. The cost per hour for a geophysical team including equipment and interpretation is about $75 to $85 per hour. To obtain total costs, the time from Table 6(c) is multiplied by $80. This figure does not include travel costs, per diem, or additional time required in difficult terrain.

Well Construction

Most methods for sampling the saturated zone require wells. Where no wells or other devices exist for sampling the saturated zone, well construction must be considered. Wells can be constructed by the following principal methods: (1) dug, (2) augered, (3) driven, (4) jetted, and (5) drilled. The first four methods are usually employed for shallow wells (150 feet deep or less), while drilling techniques are used for both shallow and deeper wells. These five methods and the physical characteristics of wells are described in detail by Johnson (1971), Anderson (1967), Bowman (1911), Gibson and Singer (1971), the U.S. Departments of the Army and Air Force (1957), the California Department of Water Resources (1968), and Campbell and Lehr (1973).

Types of Shallow Wells

Dug wells are excavated by hand or power shovel to depths usually ranging from about 10 to 40 feet. These wells commonly are about 5 to 8 feet in diameter and extend only a few feet below the water table. The shaft may

TABLE 6. EARTH RESISTIVITY SURVEY COSTS, DECEMBER 1974

Depth to top of plume (ft)	Thickness of plume (ft)		
	20	50	100
20	60	100	150
50	90	130	200
100	150	200	250
200	260	300	350
500	560	600	700

(a) Determination of electrode spread to cover depth of plume.

Electrode spread	Areal extent of plume (acres)			
	20	50	100	1000
60	4	8	12	20
90	4	8	12	20
100	3	6	10	15
130	3	6	9	15
150	3	5	8	13
200	2	4	7	10
250	2	4	7	10
260	2	4	7	10
300	2	4	5	8
350	2	4	5	8
560	2	3	4	6
600	2	3	4	6
700	2	3	4	6

(b) Determination of number of surveys to cover area of plume.

Electrode spread from (a)	Time (hrs)	Number of survey from (b) × time (hours)			
		20 acres	50 acres	100 acres	1000 acres
60	2	8	16	24	40
90	2	8	16	24	40
100	3	9	18	30	45
130	3	9	18	27	45
150	3	9	15	24	39
200	4	8	16	28	40
250	4	8	16	28	40
260	4	8	16	28	40
300	6	12	24	30	48
350	6	12	24	30	48
560	8	16	24	32	38
600	8	16	24	32	38
700	10	20	30	40	60

[a] Survey cost = $80 per hour × survey time.

(c) Determination of time (hours) and costs ($) to conduct surveys.[a]

be lined with concrete rings, stone, brick, or wood. Dug wells are used mostly for rural water supplies or for drainage water disposal, and can be polluted relatively easily because large surface openings are generally present. Such large diameter wells are not ordinarily necessary for monitoring groundwater quality.

Shallow wells may be augered by hand or power equipment. Hand augers can be used to penetrate clay, silt, and sands where cave-in will not occur in an open hole. These holes are generally not economical when depths greater than about 10 to 20 feet are encountered. In power augering by the rotary bucket method, the bucket is filled with cuttings and raised to the surface for dumping. In continuous-flight augering, the cuttings rise to the surface on rotating spiral flights. The wall of an uncased auger hole usually collapses below the water table after the auger is removed. Therefore, a drive pipe and attached well point are commonly set in the open hole and driven below the water table to the required depth immediately after the hole is drilled. Where hollow stem augers are used, a 2-inch pipe and well point can be set inside the hollow stem to the required depth. (Vertical movement of water can occur in the annular space between the wall of the drilled hole and the well casing.) Monitoring wells to depths of 150 to 200 feet can be sunk quickly in unconsolidated deposits by use of a power auger. The size of an auger hole may range from 2 to 32 inches in diameter. Auger holes may be of great value in monitoring relatively shallow polluted zones in unconsolidated deposits.

Driven wells (sometimes called sandpoint wells) generally consist of a casing 1-1/4 to 2 inches in diameter and an attached drive point. The drive point consists of perforated pipe with a steel point at its lower end to break through pebbles or thin layers of hard material. These are installed to depths generally up to 30 feet and usually cannot be pumped at rates greater than a few tens of gallons per minute. Larger wells (up to 4 inches in diameter) can be driven, however, and pumps installed inside the casing. The chief disadvantages of driven wells are that construction is slow and difficult when tightly compacted materials are encountered, driving is destructive to the well itself, and yields are small. However, they are useful for monitoring shallow aquifers in unconsolidated rock.

The jetting method employs a high-velocity stream of water to drill a hole in the earth. The water stream loosens earth materials and washes the finer particles upward and out of the hole. The jetting method is most successful in sandy soils with shallow water tables. The technique is ineffective against hard rock and boulders; tight clay and hardpan also present problems. Water is commonly used in jetting wells, but a jetting fluid of greater viscosity and weight can be made by mixing clay or bentonite with water. The casing is usually sunk as the jetting proceeds, and if too much resistance is encountered, the casing may be driven. A screen may be attached to the casing during drilling or installed after the casing is driven to the final well depth. Jetted wells are generally of small diameter and less than 150 feet deep.

Costs of Shallow Wells

Monitor wells which are 2 to 4 inches in diameter and less than 200 feet deep can be installed at relatively nominal cost as shown by Figure 18. The cost of the first well is heavily weighted by the cost of transportation and setting up of the equipment. The cost of a second well, assuming it is located close by, is considerably less. The costs represented in Figure 18 represent the average of auger and jet methods and include 2-inch diameter polyvinyl chloride (PVC).

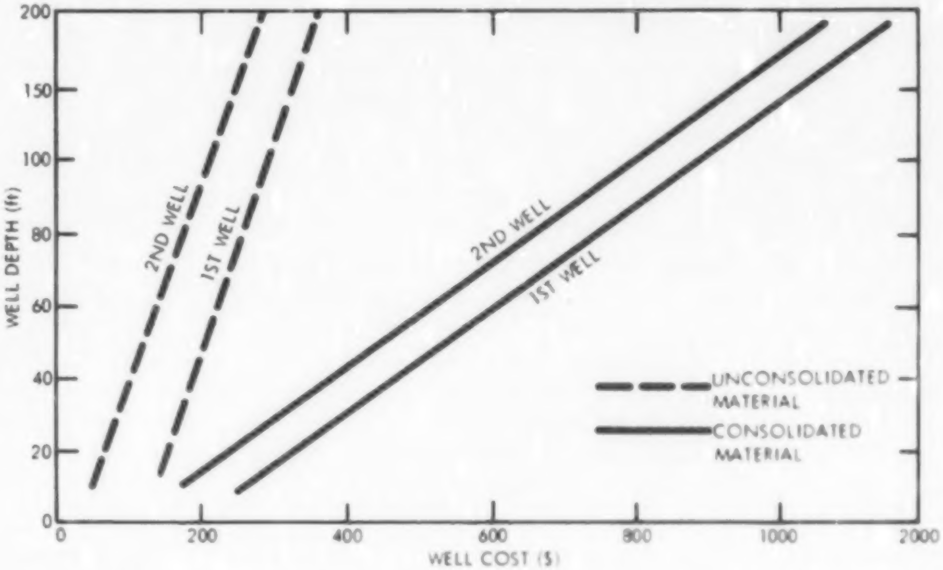

Figure 18. Cost of shallow, small-diameter monitor wells, October 1974.

Types of Drilled Wells

Drilled wells are constructed by the cable tool (percussion) method or by rotary methods. The relative merits of the various methods of drilling vary, and no one method is superior under all conditions.

In the cable tool method, the hole is formed by the percussion and cutting action of a drilling bit that is alternatively raised and dropped. The drill cuttings are removed at intervals by a bailer or sand pump. An open hole can be drilled in consolidated rock, but in unconsolidated formations, casing is driven down the hole during drilling. Above the water table, water is added to the hole so that the cuttings can be readily bailed. The bottom of the casing is fitted with a heavy-walled, hardened steel drive shoe. As the casing is driven in unconsolidated formations, frictional forces increase until the casing cannot be sunk further without the use of special tools.

Small cable tool rigs can usually drill a 5-inch diameter hole to a depth of about 300 feet. The largest cable tool rigs can drill a 5-inch diameter hole to a depth in excess of 7000 feet. With medium and high capacity rigs, 18- to 24-inch diameter holes are commonly drilled to depths of several hundred feet. The major disadvantage of cable tool drilling is its slow drilling time and depth limitation; however, the latter is well below the monitoring depths for most types of groundwater pollution.

Sampling and logging of geologic formations are simpler and more accurate for the cable tool method than for most other drilling methods. The samples are not contaminated by drilling mud, and clay, shale, and silt fractions are not likely to be lost by dispersion in a drilling fluid. When a potential aquifer is encountered, it may be tested by bailing or pumping. The mobility of cable tool rigs give them an advantage in rugged terrain and in isolated areas. Cable tool rigs can usually drill through fractured, fissured, broken, or cavernous rocks. The method requires much less water for drilling than most others, which is an important consideration in arid areas.

A major advantage of the method for water quality monitoring is that water samples can be obtained by bailing as each stratum is opened to the bottom of the casing and upper strata are cased off. The water-bearing characteristics and static heads of various strata can also be determined as the casing is being driven. Special methods have been developed for assuring a tight seal around the casing.

Rotary drilling, used for oil wells, has virtually no depth limit for most fresh groundwater systems. A variant method, reverse-circulation rotary drilling, is also used. The rotary method is distinguished from the reverse-circulation method by pumping a drilling fluid through the inside of the drill pipe and out through the openings in the bit. The drilling fluid is a suspension of solids in liquids and commonly is termed "mud." The drill stem is rotated as a downward force is applied, and the mud flows back to the surface through the annulus between the drill pipe and the hole wall. The mud cools the bit, transports cuttings to the surface, and maintains hole stability.

The drilling fluid contains solids, the make-up water, and additives, all of which may introduce contaminants into the system. Mud additives are used to make the mud thicker, thinner, or heavier, or to otherwise adapt it to special conditions. Bentonite is one of the most common additives.

New drilling mud additives have been developed in the water-well industry. One such additive is a biodegradable material which does not contaminate water-bearing sands with clay particles and can be totally removed from the well during development.

In unconsolidated deposits, the casing (and screen, if used) are installed in a rotary hole after the final drilled depth is reached. The well is then gravel-packed and developed. Gravel packing is done to minimize problems of sanding and to improve the rate of inflow of water. Well developing is done by various methods, with the primary purpose being to clean out drilling mud that has entered the formation during drilling.

Direct-circulation (conventional) rotary drilling may be less desirable than cable-tool for test-hole drilling. Drill cuttings tend to be mixed from different depths and contaminated by drilling mud. The characteristics of drilling mud may be time-variable so that cuttings brought to the surface can vary with mud characteristics, rather than with where the material was penetrated. Sample time lag in deeper holes can also become troublesome in obtaining a reliable geologic log. Measuring static water levels, taking representative water samples, and performing pump tests of individual aquifers during drilling are often not practical with rotary drilling.

The principal advantages of the direct-rotary method are speed, great depth capability, and the ability to run electric logs in an open hole prior to casing installation.

In the reverse-circulation rotary method, the drilling fluid is muddy water instead of drilling mud and is introduced down the hole outside of the drill pipe. The drill cuttings are pumped up through the drill pipe as drilling proceeds and are separated from the drilling fluid at the surface. From 20 to 500 gallons per minute (gpm) of make-up water, depending on the hole diameter, may be needed at times when drilling through highly permeable sediments.

The air rotary method is similar to the other rotary methods, except that compressed air is used instead of drilling mud to bring the cuttings to the surface. Mud or other chemical sealants may be required where the materials are loose and tend to cave. The conventional drill bit can be replaced with a pneumatic drill bit which speeds up the drilling by pulverizing the consolidated rock.

Costs of Well Drilling

Well-drilling costs vary depending on such factors as site accessibility, labor and material costs, type of well design, use of the well, degree of development, yield, and local geologic conditions. Bids submitted in connection with well-construction contracts may be itemized or may simply quote a lump-sum charge. Itemized bids generally show unit prices for (1) moving in and setting up the rig, (2) drilling, (3) casing, (4) screen or perforated casing, (5) grouting the annular space, (6) coring, (7) developing time, (8) pumping test, and (9) geophysical logging. Providing and installing pumps, pump houses, and controls are additional items whose combined cost, especially in the case of public-supply wells, may exceed the cost of constructing the well. Many of these items, however, can be neglected for small observation wells.

In a well-construction program, the cost of drilling can be separated from well development and can be generally approximated. The cost of drilling will vary primarily with hole diameter, type of geologic formation, and depth of well. Drilling costs for 40- to 1000-foot depths in unconsolidated formations for various well diameters are given in Table 7. Similarly, drilling costs for consolidated formations are given in Table 8. Although these drilling costs are very general, they do provide a first approximation. It is common for drillers to drill hole sizes from 4 to 27 inches. The well-drilling costs provided in Tables 7 and 8 are averages for EPA Regions III and IV, but drilling costs do not vary as much across the country as casing and pump costs.

Well Casing and Costs

Campbell and Lehr (1973) summarized five types of pipe used in the water well and plumbing industries: (1) standard pipe, (2) line pipe, (3) reamed and drifted pipe, (4) drive pipe, and (5) water-well casing. Water-well casing is a thin-walled, fine-threaded casing differing in dimensions and threads from all other types of pipe. Thread dimensions vary among different types of pipe. An improper joint and possible casing failure can result if threading specifications are not adhered to. Specifications for water-well casing often designate ASTM A-120 and ASTM A-53. American Petroleum Institute (API) casing is designated by the outside diameter and the wall thickness. The size and weight of the casing must be designed to assure that drilling tools, well screens, pumps, etc. can be inserted. Water-well casing is often selected on the basis of its resistance to corrosion.

Black pipe is used for small-diameter wells since water-well casing is not made below a 4-inch diameter. Four- to 6-inch diameter wells are about the smallest size that will handle a submersible pump. These small-diameter black pipe casing costs are given in Table 9. It can be seen that the cost of black pipe in shallow wells compares closely with the drilling costs in unconsolidated formations. On the other hand, polyvinyl chloride (PVC) casing is becoming more popular and is available at less cost (Table 10). While the cost of small-diameter casing is more competitive than large-diameter casing, these costs can vary with time and regional location.

Some wells are essentially open holes drilled into consolidated rocks and may have only a short length of casing near the land surface. In wells in

TABLE 7. COSTS IN DOLLARS FOR WELL DRILLING IN UNCONSOLIDATED FORMATIONS, EPA REGIONS III AND IV, OCTOBER 1974

Well hole diameter (in)	Depth of well (ft)																
	40	60	80	100	140	180	200	240	280	300	350	400	500	600	700	800	900	1000
16	800	1200	1600	2000	2800	3600	4000	4800	5600	6000	7000	8000	10,000	12,000	14,000	16,000	18,000	20,000
14	700	1050	1400	1750	2450	3150	3500	4200	4900	5250	6125	7000	8750	10,500	12,250	14,000	15,750	17,500
12	600	900	1200	1500	2100	2700	3000	3600	4200	4500	5250	6000	7500	9000	10,500	12,000	13,500	15,000
10	500	750	1000	1250	1750	2250	2500	3000	3500	3750	4375	5000	6250	7500	8750	10,000	11,250	12,500
8	400	600	800	1000	1400	1800	2000	2400	2800	3000	3500	4000	5000	6000	7000	8000	9000	10,000
6	300	450	600	750	1050	1350	1500	1800	2100	2250	2625	3000	3750	4500	5250	6000	6750	7500
5	250	375	500	625	875	1125	1250	1500	1750	1875	2188	2500	3125					
4	200	300	400	500	700	900	1000	1200	1400	1500	1750	2000	2500					
3	150	225	300	375	525	675	750	900	1050	1125								
2	100	150	200	250	350	450	500	600	700	750								
1	50	75	100	125	175	225	250	300	350	375								

TABLE 8. COSTS IN DOLLARS FOR WELL DRILLING IN CONSOLIDATED FORMATIONS, EPA REGIONS III AND IV, OCTOBER 1974

Well hole diameter (in)	Depth of well (ft)																	
	40	60	80	100	140	180	200	240	280	300	350	400	500	600	700	800	900	1000
16	640	960	1280	1600	2240	2830	3200	3840	4480	4800	5600	6400	8000	9600	11,200	12,800	14,400	16,000
14	560	840	1120	1400	1960	2520	2800	3360	3920	4200	4900	5600	7000	8400	9800	11,200	12,600	14,000
12	480	720	960	1200	1680	2160	2400	2880	3360	3600	4200	4800	6000	7200	8400	9600	10,800	12,000
10	400	600	800	1000	1400	1800	2000	2400	2800	3000	3500	4000	5000	6000	7000	8000	9000	10,000
8	320	480	640	800	1120	1440	1600	1920	2240	2400	2800	3200	4000	4800	5600	6400	7200	8000
7	280	420	560	700	980	1260	1400	1680	1960	2100	2450	2800	3500	4200	4900	5600	6300	7000
6	240	360	480	600	890	1080	1200	1440	1680	1800	2100	2400	3000	3600	4200	4800	5400	6000
5	200	300	400	500	700	900	1000	1200	1400	1500	1750	2000	2500					
4	160	240	320	400	560	720	800	960	1120	1200	1400	1600	2000					
3	120	180	240	300	420	540	600	720	840	900								
2	80	120	160	200	280	360	400	480	560	600								
1	40	60	80	100	140	180	200	240	280	300								

TABLE 9. BLACK PIPE CASING COSTS FOR WELLS IN DOLLARS, EPA REGION IX, OCTOBER 1974

Standard well-black pipe diameter (in)	Depth of casing (ft)																	
	40	60	80	100	140	180	200	240	280	300	350	400	500	600	700	800	900	1000
6	335	502	670	837	1172	1507	1674	2009	2344	2511	2930	3348	4185	5022	5859	6696	7533	8370
5	264	397	529	661	925	1190	1322	1586	1851	1983	2314	2644	3305					
4	190	285	380	472	665	855	950	1140	1330	1425	1662	1900	2375					
3	126	188	251	314	440	565	628	754	899	942								
2	61	92	122	153	214	273	306	367	428	459								
1	29	43	58	72	101	130	144	173	202	216								

TABLE 10. PVC PIPE COSTS FOR WELLS IN DOLLARS, EPA REGION IX, OCTOBER 1974

Well casing diameter (in)	Depth of casing (ft)																	
	40	60	80	100	140	180	200	240	280	300	350	400	500	600	700	800	900	1000
10	347	520	694	867	1214	1561	1734	2081	2428	2601	3035	3468	4335	5202	6069	6936	7803	8670
9	286	428	571	714	999	1285	1427	1713	1998	2141	2498	2854	3568	4281	4995	5708	6422	7135
8	224	336	448	560	784	1008	1120	1344	1568	1680	1960	2240	2800	3360	3920	4480	5040	5600
7	178	267	356	445	623	801	890	1068	1246	1335	1558	1780	2225	2670	3115	3560	4005	4450
6	132	198	264	330	462	594	660	792	924	990	1155	1320	1650	1980	2310	2640	2970	3300
5	93	140	186	233	326	419	466	559	652	699	816	932	1165					
4	61	91	122	152	213	274	304	365	426	456	532	608	760					
3	37	55	74	92	129	179	184	221	258	276								
2	17	25	34	42	59	76	84	101	118	126								

unconsolidated deposits, the hole must be cased to the bottom. Standard-weight pipe is usually adequate for depths where casings of 6-inch diameter or less are set.

Special types of casing may be needed in areas of certain groundwater qualities and geologic characteristics. Cupronickel alloys are most suited for sea-water production wells. Carbon steel has demonstrated a high resistance to soil corrosion. Stainless steel offers considerable durability and high reliability.

Plastic casing has increased in use recently. Maximum installation depths for PVC pipe are normally less than 200 feet. Rubber-modified polystyrene has also been used as well casing, but is not recommended for depths greater than 300 feet. Plastic well casings are usually not larger than 6 inches in diameter for structural reasons. However, fiberglass-reinforced, epoxy pipe has more desirable characteristics than pure plastics; 8- and 10-inch sizes have been used extensively to depths of about 300 feet for water-well casing. Epoxy plastic pipe has a high resistance to corrosion and reduced incrustation problems.

Wells in highly corrosive environments are sometimes cased with ceramic tile, concrete, asbestos cement, or even wooden pipe, but most of these are heavy, structurally weak, and are not readily available in many areas. Concrete and asbestos-cement pipe are subject to rapid deterioration in high-sulfate soils and water.

Well Screens and Perforated Casing

When completing most wells in unconsolidated materials, openings in the casing must be provided to permit entrance of water. In some areas no perforations are used and the pipe is left open, whereby water is drawn through the end of the casing. In areas of relatively thick water-producing strata, the casing is commonly perforated over intervals up to several hundreds of feet. Casings can be perforated in the field by torch or can be factory perforated. Down-hole perforators can be used for blank casing already in a well. Slotted casing has an open area of about 1 percent for 0.030-inch slots to about 12 percent for 0.250-inch slots. Factory perforated casing usually has an open area ranging from 4 to 18 percent.

A specialized piece of equipment, known as a well screen, has been developed for maximizing the open area percentage. For cage type, wire-wound screens, the open areas range from about 2 percent for 0.0006-inch slots to over 60 percent for 0.150-inch slots. Well screens may be made of iron, fiberglass, brass, stainless steel, or PVC. Well screens are especially applicable to sampling relatively thin (less than 50 feet thick) sections of the aquifer.

The sizes of perforations, slots, or screen openings are chosen with respect to particle size distribution of the water-bearing zones. Entrance velocity into the screen or perforated casing is usually recommended to be less than 0. 1 to 0. 2 feet per second. The amount of open area desired can be calculated based on well discharge.

Gravel Packing

In a naturally developed well, the development process removes finer material from the vicinity of the perforations or screen, leaving a zone of coarser graded material around the well. This cannot be achieved in a formation consisting of a fine uniform sand, due to the absence of any coarser material. The object of gravel packing a well is to artificially provide the graded gravel or coarser sand that is missing from the natural formation.

Two conditions in unconsolidated materials tend to favor gravel packing: (1) fine uniform sand, and (2) extensively layered deposits. The latter condition is common in alluvial fan deposits of the Southwest. The selection of the grading of the gravel pack is usually based on the finest material in the aquifer.

Gravel packing is also used for formation stabilization. Since drilling by the rotary method through unconsolidated materials of necessity results in a hole somewhat larger than the outside diameter of the casing, the annular space around the well screen is gravel packed to prevent silt and clay above the water table from caving or slumping into the well producing zone.

Screen openings or perforations are chosen so as to retain 90 percent or more of the gravel-pack material. The gravel pack should consist of clean, well-rounded, smooth grains. Quartz and other silica-based materials are preferable. Gravel-pack envelopes are usually 3 to 8 inches thick.

Well Sealing

Grouting well casing involves filling the space around the casing with a suitable slurry of cement of clay and sand. Isolation by grouting is desirable to protect the producing zone from contamination by less desirable fluids from other levels or from the surface. Cementing materials include portland cement, bentonite, pozzolana, perlite, diatomaceous earth, Gilsonite, and mixtures of these.

To assure that grouting provides a satisfactory seal, the slurry must be added continuously to prevent cold joints. The grout should be introduced at the base of the grouting interval to minimize contamination or dilution of the slurry and bridging of the mixture with upper formation material. The grout is usually pumped into the space to be filled; however, placement by gravity is satisfactory in some cases.

An increasing number of States are establishing requirements on sealing wells to protect them against contamination by surface waters. In this case a near-surface, upper annular-space seal of an aggregate of fine sand and cement is commonly used. This type of seal generally extends from 10 to 50 feet or more in depth.

Well Development

The well is developed after it has been drilled, cased and packed. The object of well development is to remove silt, fine sand, and other such material from a zone immediately around the well. This creates larger waterflow passages in the formation around the well.

Well development corrects clogging or compaction of the formation which occurs during drilling. Drilling mud used in the rotary method effectively seals the face of the borehole. All drilling methods do some damage to the formation, and well development is used to correct this damage. Well development also grades the material in the aquifer immediately around the casing in such a way that a stable condition is achieved in which the well yields sand-free water at maximum capacity.

To be effective, the development operation must cause reversals of flow, or surging, through the perforation or screen openings. This is necessary to avoid the bridging of openings by groups of particles that can occur when the flow is continuously in one direction. The reversals of flow are caused by forcing water out of the well through the screen or perforations and into the aquifer, then removing the force to allow flow to occur from the aquifer back into the well.

Mechanical surging is the name given to a process of operating a plunger up and down in the casing like a piston in a cylinder. The tool used is called a surge plunger or surge block. Before surging, the well should be washed with a jet of water and bailed or pumped to remove the drilling mud cake on the face of the borehole. Dispersing agents, mainly polyphosphates, are added to the water in the well to counteract the tendency of the mud to stick to sand grains. These agents are often applied at the rate of one-half pound to every 100 gallons of water in the well. Materials brought into the well by surging can be periodically removed by bailing. Surging can also be achieved by alternately turning the test pump on and off.

High-velocity jetting, or backwashing of an aquifer with high-velocity jets of water directed horizontally through the screen openings, is generally the most effective method of well development. The energy of the jets can be concentrated over small areas at any particular time and all of the screen or perforated area can be selectively treated. Thus, uniform and complete development is achieved throughout the length of the perforated interval or well screen.

Test Pumping

Test pumping is commenced upon completion of well development operations. Often the well is pumped at low rates during early phases of the test and high rates at later phases. Periodic surging may be necessary if the well does not appear to be developed. Often the well is pumped at a much greater rate than that intended for use. This further acts as a well development procedure. By increasing well discharge in a step pattern, a step-drawdown test can be run. This can be followed by a constant discharge test. In alluvial aquifers, pump tests of 24 to 72 hours may be sufficient. For aquifer analyses in consolidated rocks, pump tests from 1 week to 1 month or longer may be advisable. Pump testing for aquifer analysis requires consideration of aquifer geometries as well as inhomogeneities and anisotropies in the aquifer.

Total Well Construction Costs

While general data have been provided for drilling and casing costs, additional costs such as for screens, gravel packing, grouting, well development, etc. are highly dependent upon local conditions. It is therefore more appropriate to provide separate cost data for completed wells in sand and gravel and wells in consolidated formations. Detailed well cost analyses have been done by Cederstrom (1970) and Gibb (1971).

Gibb provides a total cost analysis for small-diameter domestic and farm wells. Since these small bore wells approximate the size of most monitor wells, these cost data are presented here. Cost information for 345 wells of various types constructed in sedimentary rocks throughout Illinois during 1967, 1968, and 1969 was collected by Gibb. All data were adjusted to a common 1969 economic level by using a domestic and farm well index developed as a part of the study. This index, shown earlier as Figure 2, indicates the increase in the costs of farm and domestic wells in Illinois from 1913 through 1969. Figure 2 also illustrates the increase in costs of large-capacity wells. It can be seen that the small-diameter domestic and farm well index closely follows the materials component of the Engineering News-Record.

Recent applications of the materials component to Gibb's cost data closely approximate the current cost of small-diameter wells. For this reason his data have been updated to March 1975 using the materials component of the Engineering News-Record. Well-cost data were divided into two categories by Gibb, according to the aquifer tapped and the type of well construction. Thus, commercially screened, drilled wells completed in water-bearing sand and gravel deposits are shown in Figure 19, while drilled wells completed in water-bearing sandstone, limestone, and dolomite of consolidated bedrock formations are shown in Figure 20.

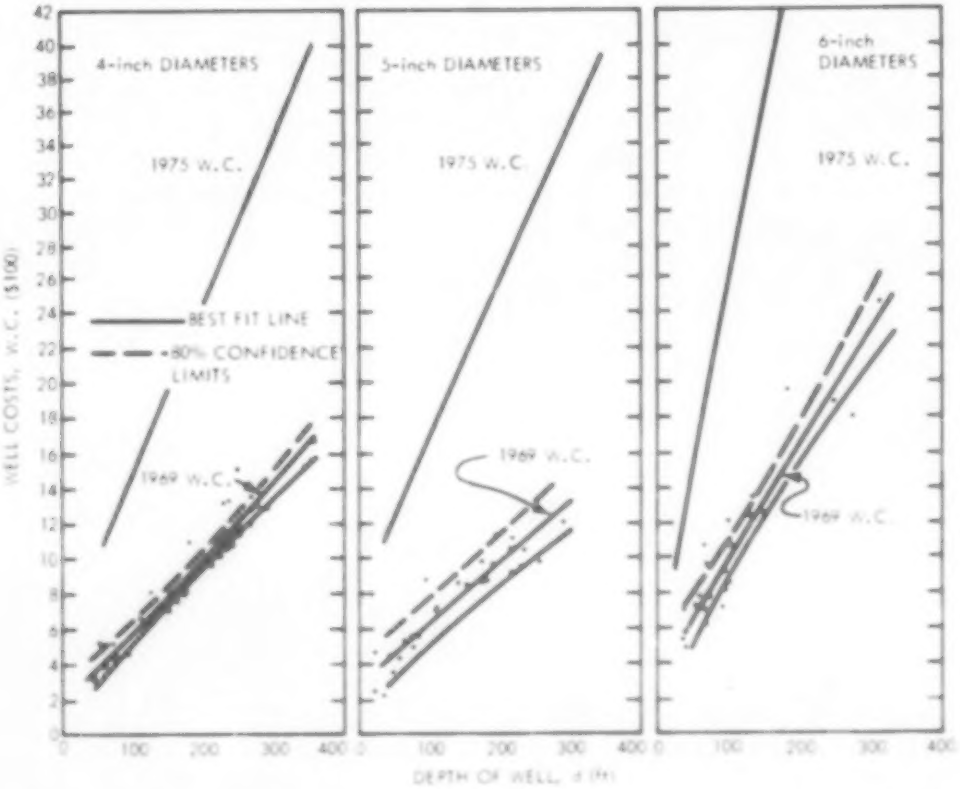

Figure 19. Updated (1975) cost of 4-, 5-, and 6-inch wells in sand and gravel (after Gibb, 1971).

The final sets of data may include materials and/or labor cost for the following:

1. Setting up and removing the drilling equipment
2. Drilling the well
3. Installing casings and liners
4. Grouting and sealing the annular spaces between casings and boreholes
5. Installing well screens and fittings
6. Developing the well.

Test Drilling

Test holes can be drilled to permit water sampling of polluted groundwater. For diffuse sources of pollution, existing wells can often be used. Near point or line sources of pollution, test holes can also be used for

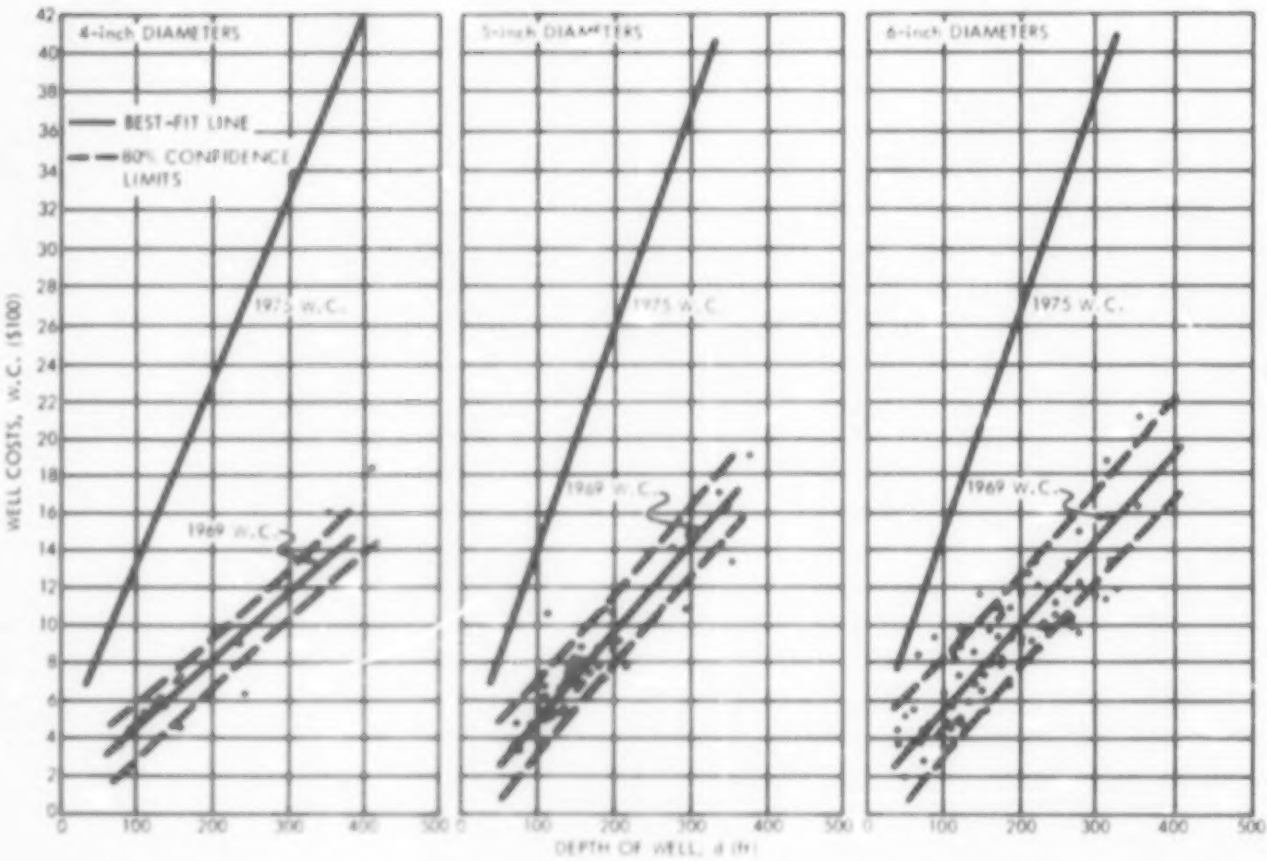

Figure 20. Updated (1975) cost of 4-, 5-, and 6-inch wells in consolidated rock (after Gibb, 1971).

delineation of subsurface lithology, water level information, determination of aquifer parameters, and sampling of geologic materials. Test holes and subsequent water sampling and analysis is the most direct method of monitoring groundwater pollution where existing wells are insufficient in number. The location, method of construction, well specification, and density of monitor wells for a given polluted zone depend upon local conditions.

Geological Sampling

Campbell and Lehr (1973) have provided a summary of formation identification and evaluation. The success of a well depends largely upon the degree of care used in obtaining geologic samples. Sampling materials in the saturated zone is used where significant pollutants have been retained in this zone. This will generally occur in cases of shallow water tables (thin vadose zone), or where the vadose zone is bypassed, such as in deep well disposal. The primary strata of interest will usually be the finer grained deposits, such as silt or clay, because of their ability to retain certain pollutants.

Cable-tool rig samples are usually representative of the interval drilled between bailing operations. Some contamination of the cuttings occurs in unconsolidated materials due to the cable rubbing against the upper, uncased part of the hole. When fine-grained saturated sands and silts are encountered, care must be used in bailing to avoid heaving materials into the hole.

Rotary rig samples are usually collected at regular intervals. These samples contain some cavings and fragments circulated in the drilling mud. Differential settling occurs between light and heavy fragments in the drilling mud and this leads to complications in logging. The collection of samples at the surface lags behind the actual cutting of a given stratum at depth. This lag may amount to more than 20 feet in a 300-foot hole. This lag depends upon the pump size and speed, the hole size, the drill pipe ID, and the viscosity of the drilling fluid. An electric log can be used in conjunction with a geologist's log to provide information on the time lag. Rotary rig samples from unconsolidated materials may be poor, particularly when relatively thin layers of sand, gravel, and clay are being drilled. Soft clays become dispersed in the drilling mud and are difficult to ascertain. Coring is recommended in such strata.

Samples obtained from compressed-air rotary drilling are generally superior to those from other methods. Casing is usually necessary in order to minimize contamination if soft, fine-grained material is higher in the hole.

Excellent samples can be collected during drilling with reverse-circulation rotary rigs. The highly turbulent fluid velocities up the drill stem result in little or no separation of the fines with a minimum time lag. The bit tends to loosen materials rather than grind them up, and the cuttings are drawn into the bit and delivered at the surface.

Coring is a sampling method as well as a drilling method. It is usually done with rotary equipment and individual cores are often less than 4 inches in diameter and 10 feet in length. Numerous rock types can be successfully cored with any core bit, but soft and friable formations are difficult to core.

Unconsolidated deposits of interbedded soft clays, sand, and gravel are usually difficult to core. However, a split-core, drive sampler will often provide excellent samples of these materials. A number of coring devices are available, ranging from 1-1/2 to 6 inches in diameter. These devices may be forced into the deposits by the weight and rotation from the rotary rig or by "drive coring" with the cable-tool rig. Barton (1974) reports on borehole sampling of saturated unconsolidated sands and gravels. A great variety of samplers have been specially designed for these materials. In extreme situations it may be necessary to stabilize the strata prior to sampling. Sidewall sampling is gaining wider application for unconsolidated materials.

Drilling mud should be avoided if possible when sampling formations for groundwater pollution studies. Air rotary and reverse-circulation rotary drilling methods are preferable since neither method requires the use of drilling "additions." Cable-tool drilling is also useful, but relatively slow. In-place samples are extremely important in aquifer evaluation of permeability and other considerations. Intact, in-place samples are less important in chemical quality and pollution studies; that is, geologic samples can be physically disturbed to some degree.

The cost of obtaining geologic samples other than by coring is primarily a function of the time spent by the geologist who does the logging. Registered geologists charge about $150 to $250 per day for their services. Coring services vary with the kinds of rigs used, the core diameter, and the sampling frequency. A generalized cost diagram is given in Figure 21. The cost figures are generalized to cover small-diameter coring (2 to 3 inches) for shallower depths and larger coring sizes (3 to 5 inches) for deeper samples, since larger bore diameters are required when drilling to depths greater than 100 feet. The first core taken includes a 1-hour setup and travel time cost while the second includes just the drilling cost (Figure 21). It is apparent that in unconsolidated formations the travel and setup constitute a relatively larger part of sampling costs than for consolidated formation sampling. At greater depths, the time involved in taking the samples overrides the drilling time.

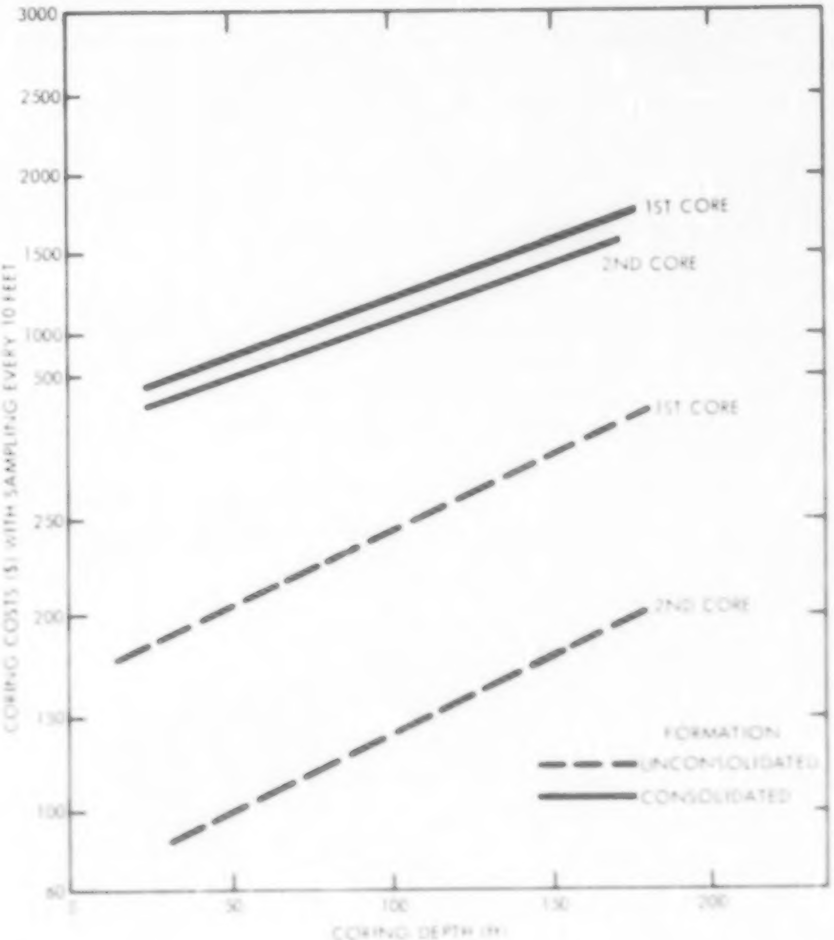

Figure 21. Generalized cost of coring in unconsolidated and consolidated formations, October 1974.

Borehole Geophysics

Geophysical well logging, or borehole geophysics, includes all techniques of lowering sensing devices in a borehole and recording some physical parameter that may be interpreted in terms of the characteristics of the rocks and the fluids in the rocks. Geophysical logs can be interpreted to determine many groundwater parameters. The single most important factor that has limited the use of geophysical logging in groundwater studies in the past is cost. Logging generally is more feasible in deeper, more expensive wells.

The electrical conductivity or resistivity of fluid in a well bore or the surrounding aquifer is one of the most useful parameters that can be derived from geophysical logs. If the chemical nature of the water in an aquifer is known from chemical analyses, and the ion ratios are consistent, resistivity or conductivity from logs can be used to determine the approximate quantities of those ions present. The relationship of water in the hole to water in the surrounding materials must be understood in order to interpret a number of geophysical logs. The chemical quality of fluid in the hole is not necessarily similar to that of fluid in the surrounding materials. After a hole is completed, it may be as much as several months before chemical and thermal equilibrium is reached.

The electric log is very useful in determining subsurface lithology and is generally the most common geophysical log run in water wells. An electric log can be run only in an uncased hole that is filled with a conducting fluid. The electric log usually includes the spontaneous potential curve in the left-hand column and one or more resistivity curves in the right-hand column. Spontaneous potential logs are records of natural potentials developed between the borehole fluid and the surrounding materials. The use of spontaneous potential for determination of groundwater quality in fresh-water aquifers is not advisable (Keys and MacCary, 1971).

Resistivity logging devices measure the electrical resistivity of a known or assumed volume of earth materials under an electric current. Normal logs measure the apparent resistivity of a volume of earth materials surrounding the electrodes. The short normal log records the apparent resistivity of the invaded zone (extent of drilling mud penetration). The long normal log records the apparent resistivity beyond the invaded zone and is useful in determining aquifer water quality. The normal logs give poor results in high resistivity rocks.

One method of estimating water quality from electric logs makes use of mathematical expressions which relate the following parameters (Turcan, 1966):

1. Field-formation resistivity factor and fluid resistivity
2. Fluid resistivity and specific conductance
3. Specific conductance and dissolved solids.

The field-formation factor is established from preexisting electric logs and water analyses. When a new well is drilled and logged, the resistivity curve is used to determine fluid resistivity in the aquifer by the use of the formation factor. This value is converted to specific conductance at standard temperature from tables or formulas. The specific conductance is then converted to dissolved solids by empirical relationships previously developed.

Electric logs can thus provide an indication of the vertical distribution of groundwater salinity at or near a specific well. However, knowledge of the chemical type of waters at different depths must be available. Interpretation of electric logs can supplement measurements of electrical conductivity made on drilling mud during drilling. For groundwater pollution studies, the tool would be applicable to polluted zones of high electrical conductivity compared to native groundwater.

A portable electric logging system can be purchased for about $6000 to $7000 with an additional cost of $3500 to $4000 for a gamma-ray option. The cost of conducting an electrical conductivity survey including interpretation is given in Figure 22. Travel costs are not included and may be an important item in remote areas.

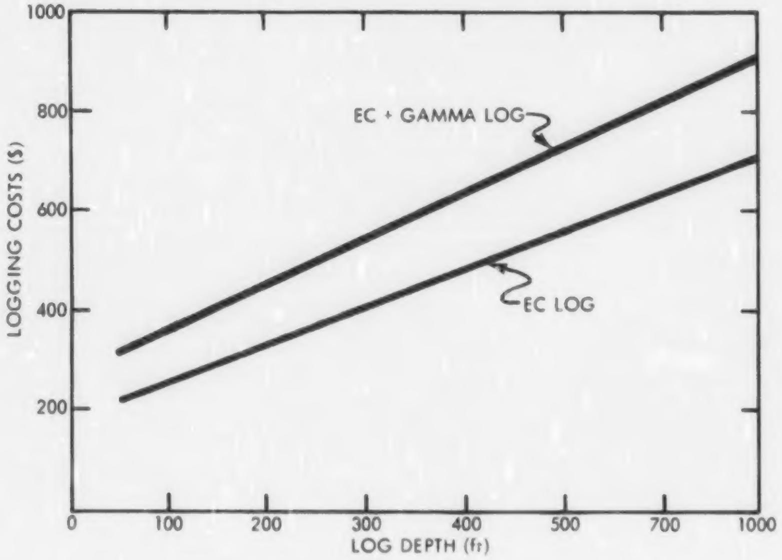

Figure 22. Cost of electrical conductivity (EC) and gamma logging, September 1974.

Water-Level Measurements

Water-level measurements for groundwater pollution studies can define a mound beneath a point source or a ridge beneath a line source. In areas with a paucity of water-level measurements supplementary measurements may be necessary to define the depth to water and the direction of groundwater movement. Water-level measurements on a regional basis contribute to the hydrogeologic framework; the discussion here will be limited to measurements in localized areas. The most common tools for measurement of water levels are the steel tape, electric sounder, airline, and mechanical recorder.

STEEL TAPE. The surveyor's steel tape has been used for many years by the U.S. Geological Survey as a water-level measuring device and is available in lengths of 100, 200, 500, and 1000 feet. Coefficients of stretch and temperature expansion are provided by the manufacturer for each tape. For most groundwater pollution studies, correction for stretch and temperature changes will not be necessary, due to the relatively shallow depths of interest. The tape is usually lowered by hand; however, in deep wells a motor-driven tape reel may be used.

The water level in a well is measured by suspending a known length of tape below a measuring point so that at least the lower few feet of tape are below the water level. The lower portion of the tape is usually coated with blue chalk or some other substance which exhibits a marked color change when wetted. The water-level measurement is obtained by subtracting the length of the wetted portion from the total length suspended below the measuring point.

One disadvantage of using the steel tape is that if the approximate depth to water is unknown, too short a length of tape may be lowered into the well, thereby necessitating a number of attempts. Also, water inside the casing or cascading water may wet the tape above the true water table and result in errors in measurement.

The number of wells measured per day depends primarily on well density, access to well sites, depth to water, well ownership, access for the measuring device, and well obstructions. For dense municipal wells under a

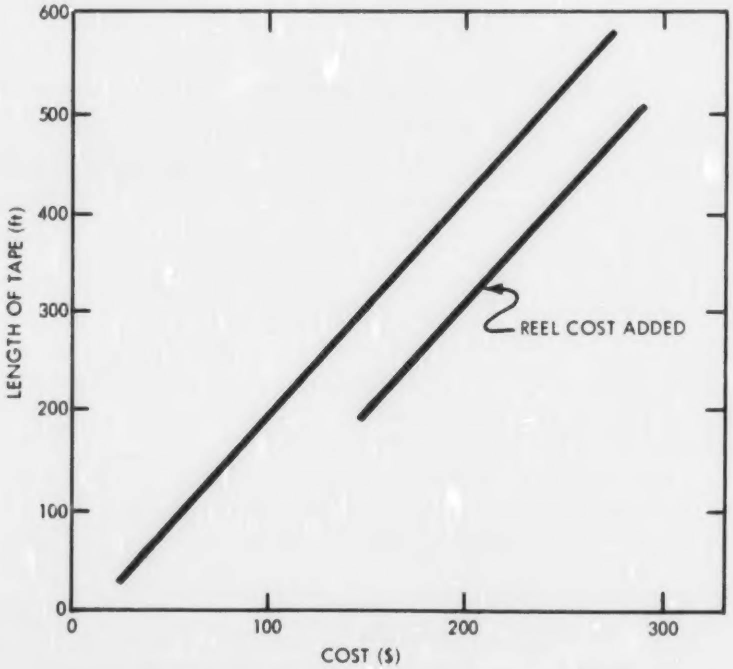

Figure 23. Cost of steel tapes, September 1974.

common manager, up to 40 to 50 water-level measurements per day can be made where the depth to water is less than 100 feet. For irrigation wells spaced at about 1/2-mile intervals in an agricultural area, about 20 to 30 water-level measurements per day can be made where the depth to water is less than 100 feet. For widely scattered stock wells in an undeveloped area, fewer than five water-level measurements may be possible in 1 day.

Measurement time is decreased considerably when the person performing the measurements is familiar with the area and the wells. For initial measurements in new programs, a much longer period of time is necessary. Prior to initiating well measurements, a comprehensive well data collection and organization program may be necessary. This provides pertinent hydrogeologic data for the wells to be measured.

Costs for steel tapes normally employed to measure water-well levels are summarized in Figure 23.

ELECTRIC SOUNDER. The electric sounder consists of a reel with a meter, one or two electric wires, and a sounding tip. The reel and meter remain at the land surface while the wire and tip are lowered down the well. A battery-powered electrode assembly is usually used; when in contact with water, it causes a sharp needle deflection on a large, sensitive current

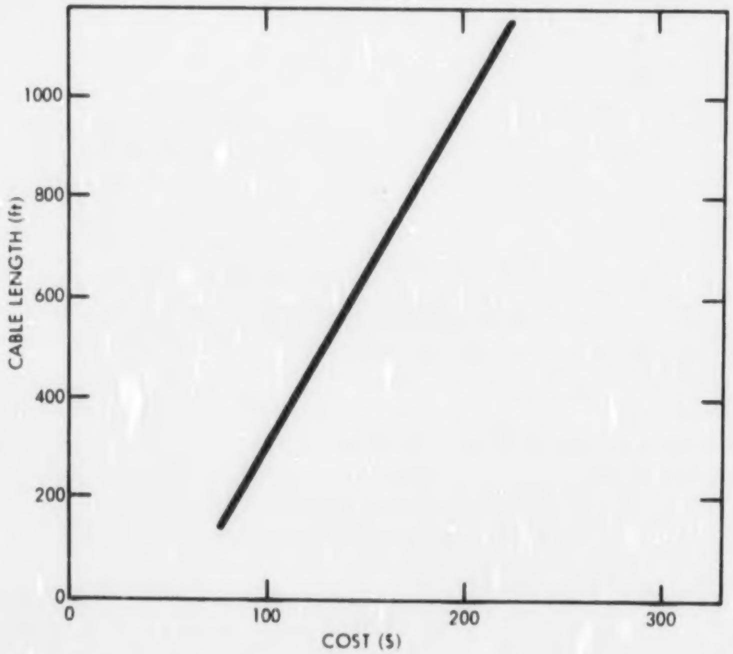

Figure 24. Cost of electric sounder and cable, September 1974.

meter. The wire is mounted on a small reel that is used for lowering and withdrawing the wire and sounding tip. Depth control is aided by metal tags on the wire.

Electric sounders are often used in pump tests where a number of measurements must be taken at small time intervals. Also, electric sounders are of great value in cases where cascading water is present. A measurement can be made in less than 5 minutes in most wells less than 100 feet deep.

The average cost of electric sounders is given in Figure 24.

AIRLINE. The airline can be a very practical device in certain situations, such as where pumping produces turbulence inside the well casing. Commonly, an airline is used by pump testers or well drillers as a rapid means to obtain water-level measurements in deep wells.

The airline consists of a small-diameter copper or iron tube which is installed in the space between the pump column and the casing. The tube is usually strapped to the pump column, and the two installed simultaneously. The airline should be free of leaks, open at the bottom, and extend several feet below the lowest pumping water level. The airline should preferably be straight and plumb, and the depth of the lower opening must be known. The top of the airline is connected to a source of compressed gas. An air-pressure gauge is used to measure the pressure in the airline.

Pressure is applied until all the water has been expelled from the airline, and the gauge can then be read. The gauge reading indicates the length of the expelled water column (the height of water above the airline opening). To obtain depth to water, the length of this column is subtracted from the length of the airline. This measurement can usually be made in several minutes.

The tubing, which is normally left in the well, may cost as little as $10. The tubing can also be installed for access by the electric sounder. The air compressor and storage tank can cost as much as $250, but a hand pump is frequently satisfactory.

MECHANICAL RECORDER. A simple recording device commonly used consists of a cylindrical recording chart actuated mechanically by a float that moves with fluctuations in the water level. A small-diameter stranded cable or tape is attached to the float, and a counterbalance is suspended over a pulley on the recorder. The pulley is geared to the chart so that the chart rotation is proportional to float movement. A clock drive slowly moves a recording pen across the chart. The mechanical recorder is used when many measurements are necessary over short time periods, and is especially useful when relatively rapid water-level fluctuations occur, such as in observation wells during pump tests. These recorders cost about $375. If a digital system rather than a chart is desired, the unit can cost about $675. Most recorders come with about 20 feet of line and an extra charge of $0.25 per foot is charged for additional line.

Garber and Koopman (1968) summarized methods of measuring water levels in deep wells. Accurate measurement of water levels deeper than 1000 feet in wells requires special equipment. Correction for stretch and thermal expansion of measuring tapes must be considered.

Water Sampling

Most of the physical factors which promote mixing in surface waters are absent or much less effective in groundwater systems. A well can be considered as a sampling point in a large body of slowly moving water, which differs in chemical composition vertically as well as areally. Unfortunately, most techniques for well sampling at discrete depths are usable only in unfinished or nonoperating wells. A more reliable means of evaluating the quality of water tapped by a well is an analysis of a pumped sample.

The volume of water that is generally collected for chemical analysis from individual widely scattered monitoring wells is relatively insignificant volumetrically. Therefore, either many more monitoring wells must be sunk or a smaller number of existing wells must be pumped at higher rates or more frequently to obtain representative values. Most wells are integrators of complex systems of surface water, soil water, and groundwater. In some cases the integrated sample is of most importance because it represents the water used, or likely to be used in the future. In other cases, an integrated sample is not of interest, but rather a sample from a specific depth zone. This requires either careful selection from existing wells or construction of special monitoring wells.

Well Hydraulics

The composition of water obtained from a well is likely to be influenced by well construction, well development, and pump operation, and these should be considered in the sampling program. Well construction can determine the depth of zones from which the water is coming and influence the local groundwater flow pattern. Perforations above the water table can permit cascading water, or direct movement of groundwater from shallow perched layers above the water table, to flow down the inside of the well to the water table. Drilling mud remaining from well construction can contain contaminants, as can well casing, seals, and pump parts.

Well hydraulics can cause chemical changes in the composition of a pumped sample. For example, pressure changes associated with velocity changes at the well inlet can cause changes in oxidation state, pH, and temperature which, in turn, affect certain chemical constituents. Thus, a sample from the well discharge may differ significantly in quality from groundwater in the aquifer. Also, in cases where chemicals are added at the discharge pipe, care must be taken to ensure the chemical composition of the sample is not altered.

Time Changes in Quality

Quality changes in groundwater are usually much slower than those in surface water. The composition of well samples from a large, relatively homogeneous aquifer usually will not change much over long periods of time. Therefore, changes in groundwater quality can be described satisfactorily by monthly, seasonal, or annual sampling schedules. However, exceptions usually occur in cases of groundwater pollution.

Just as water levels in a well change drastically soon after a pump is turned on, so can the quality of pumped water. This is particularly true where there is vertical stratification of groundwater quality. These short-term changes in some cases may be linear with pumping time, whereas in other cases they may be exponential. In the case of high-yielding wells (greater than 500 gpm), several days or weeks of pumping may be necessary to purge the well of atypical water due to local conditions. These local conditions could include poor quality, shallow water cascading down the well casing and accumulating in or near the well during nonpumping periods or vertical leakage down a gravel pack to a deeper producing zone. Often, field measurements of water temperature and electrical conductivity at the well discharge as the well is pumped can yield useful information on short-term changes in water quality. For short-term testing, consideration should be given to a logarithmic frequency of sample collection, analogous to the procedure for water-level measurements during a pump test. Short-term trends should be evaluated before adequate data are collected to determine long-term time trends in groundwater quality.

In the early days of water-level measurement programs, weekly or monthly measurements were made to discover seasonal fluctuations; elsewhere, semiannual measurements, related to high and low water levels for a year, were instituted. In some areas significant seasonal fluctuations occur in the quality of groundwater. In these areas seasonal trends must be established in the first stages of the development of monitoring programs. Specific locations where seasonal changes are likely to occur include:

1. Near large-volume point or line sources of recharge or pollution
2. Near disposal sites for highly concentrated wastes

3. In areas of permeable soils and geologic materials above the water table
4. Where wells tap shallow portions of aquifers.

Sampling at the Well Discharge

Water samples can be collected directly from pumping wells or flowing artesian wells. Nonpumping wells equipped with a pump require pumping for a substantial period after start-up to obtain a representative sample from the aquifer. In wells without fixed pumps, special portable pumps may be installed to retrieve water samples.

Water-well pumps can be classified into two groups:

1. Constant displacement pumps which deliver substantially the same quantity of water against any head within their operating capacity
2. Variable displacement pumps which deliver water in quantity varying inversely with the head against which they operate.

Major types of constant displacement pumps include: (1) piston or reciprocating, (2) rotary, and (3) screw or squeeze displacement pumps. Major types of variable displacement pumps are: (1) centrifugal, (2) jet, and (3) suction-lift pumps. A submersible pump is a centrifugal pump closely coupled with a submersible electric motor.

A pump installed above a well is called a suction-lift pump. A pump installed in the well at some depth below the water table is called a positive submergence pump. Suction lift by a pump is accomplished by developing negative pressure head at the pump intake. The maximum suction lift is limited by atmospheric pressure, vapor pressure, head losses due to friction, and the required inlet head of the pump. At sea level the best designed pumps usually achieve a suction lift of about 25 feet, while the suction lift of an average pump varies from 15 to 18 feet. The maximum suction lift decreases with an increase in altitude.

Where the depth to water is greater than the practical suction limit, a hand-operated pitcher pump, a centrifugal pump, a submersible pump, or a shallow-well jet pump is commonly used. Submersible and jet pumps require a minimum casing diameter of 4 and 2 inches, respectively. In large-diameter wells where the depth to water exceeds the suction limit, a submersible, deep-well jet, or a deep-well turbine pump is commonly used. Before a pump can be intelligently selected for any installation, information on required capacity, location, operating conditions and total head is necessary.

The time involved in sampling at the well discharge is highly dependent on whether a pump is installed and is operating, travel time between sites, and time required to gain permission to sample the wells. If the pump must be started, additional time is required.

With closely spaced, actively pumped wells in an urban area that are under the managership of only one or a few agencies, as many as 30 to 50 wells can be sampled in one day (without field analyses or treatment). In remote areas with widely spaced nonpumping wells and different owners, fewer than a half dozen samples per day may be possible.

The cost to sample each well, therefore, is a function of the travel time and man-time at each well. The salary of water sampling technicians is from $8000 to $10,000 per year. The cost to sample a number of wells under three categories of well spacings is given in Figure 25. It is assumed that a technician can sample 30 to 50 wells daily in a municipal well system, 10 to 15 irrigation wells in a rural area, and 4 to 7 in an isolated area.

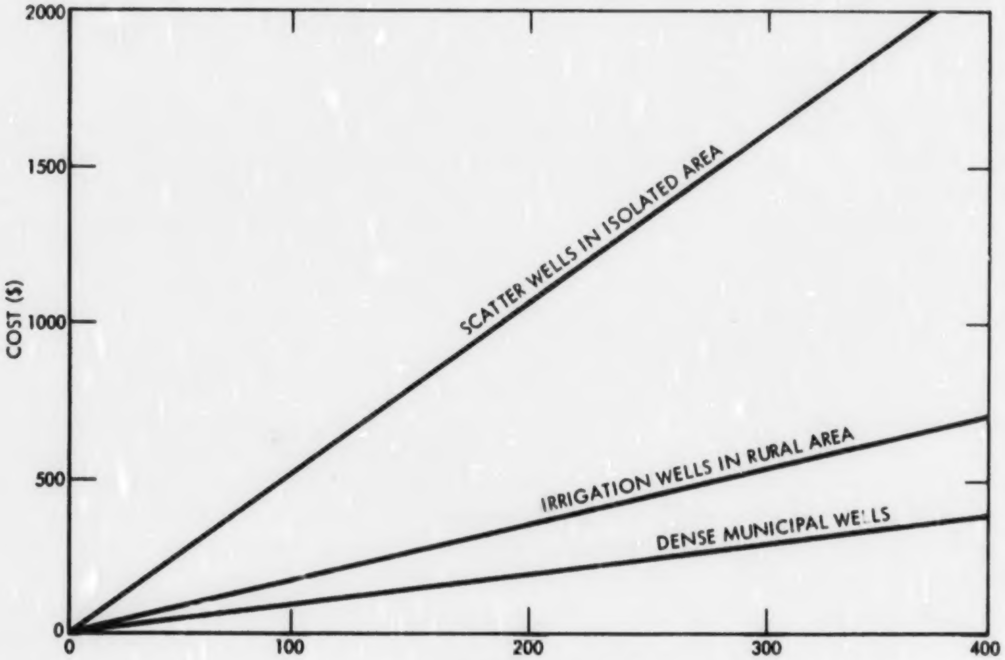

Figure 25. Approximate cost of sampling wells (one round), December 1974.

The cost of common field equipment for water quality tests is not significant over the useful life of the instruments. A portable electrical conductivity meter costs about $250 to $400. A portable pH meter can cost from

$100 to $300. Specific ion meters can be purchased for about $200 to $250, and additional probes cost about $100 to $150 each. Elaborate continuous recording, digital readout, and multiparameter water quality instruments can be quite expensive ($2000 to $3000) but are not necessary for routine water well sampling.

Types of Well Sampling

Well sampling can be grouped into two broad types: water supply and hydrogeologic. Water supply sampling is concerned primarily with the use of the water. For drinking purposes a sample might be taken from the household tap rather than from the well discharge. For irrigation purposes, a water sample might be taken from a ditch at the entrance to a field rather than from a well. Hydrogeologic sampling is concerned with natural groundwater quality or pollution. For hydrogeologic sampling, the water sample would ideally be taken directly from the aquifer, not at the well discharge. However, for practical purposes, a sample from the well discharge can be used in most cases. Ideally, high-yielding wells (greater than 500 gpm) would be used to evaluate large-scale or regional aquifer conditions; low-yielding wells would be used to evaluate local conditions.

A low-yielding well (less than 50 gpm) generally reflects water quality only in the immediate vicinity of the well. In many rural areas, for example, a domestic well would be greatly influenced by local conditions, such as lawn irrigation and septic tank waste disposal. A high-yielding irrigation well in a rural area pumped continuously would produce a water sample whose quality would reflect regional conditions, such as fertilizer application, irrigation return flow, and canal recharge.

A 5-gpm domestic well pumped daily for 1 hour produces 300 gallons in 1 day. A 3000-gpm irrigation well pumped continuously for 1 day pumps almost 15,000 times this volume of water. Erroneous interpretations have been made in past groundwater quality studies due to a lack of consideration of this factor.

High-yielding wells also can induce great vertical head differences during pumping, and this should be considered for sampling purposes. In some cases practical considerations will dictate that wells cannot be placed immediately adjacent to waste disposal sites. A sample from a high-yielding well would be more likely to show the effects of recharged wastewater because it would be more likely to induce flow toward the well. This is especially true in areas of very slow groundwater movement.

Sampling in Open Wells

In wells where a fixed pump is not available, a portable submersible pump can be used. This pump is feasible where a number of monitor wells occur in a small area and only periodic pumping is required. Samples from abandoned or inactive wells of unknown construction are often of limited value. The cost of these pumps is a function of the pump size, cable load, flex hose diameter, and sampling depth. The cost of submersible pumps for various pumping lifts and well discharges can be obtained from Table 11. In addition to the pump cost, the cost of the support cable and flex hose (Figure 26) must be added. The unit is usually placed on a power-driven reel.

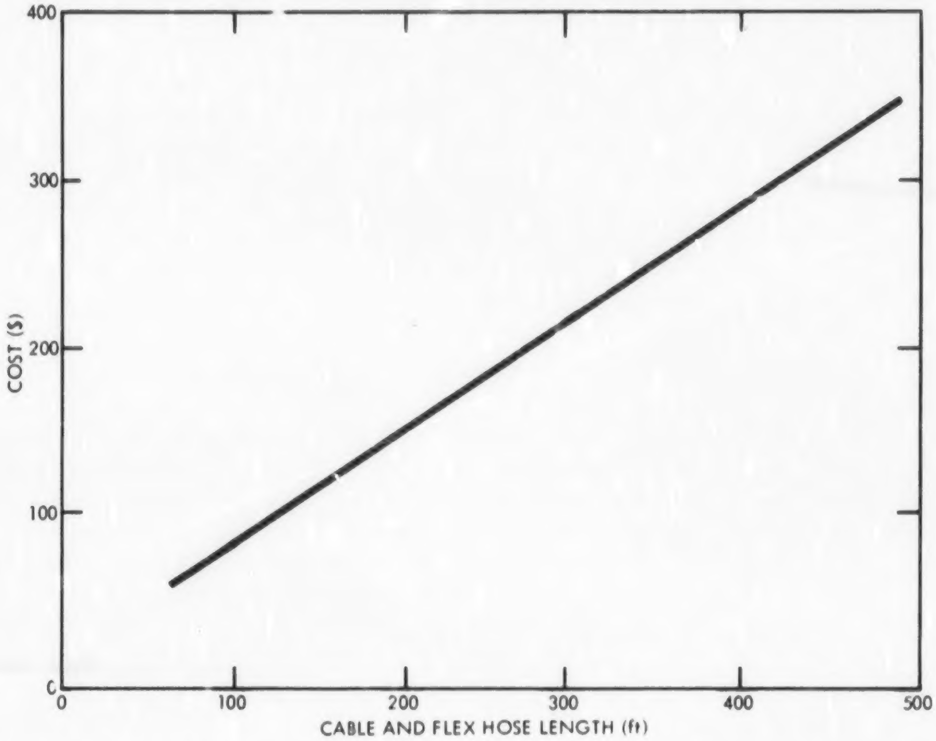

Figure 26. Cost of cable and flex hose for use with portable submersible pumps, October 1974.

The power costs to run submersible pumps are given in Figure 27. The power costs vary with the discharge rate, total head, pump efficiency, and electrical costs. Figure 27 shows that the power costs for 1 hour operation of a submersible pump are minimal. These costs include a motor efficiency of 75 to 80 percent, a pump efficiency of 70 to 75 percent, and scaled electrical costs of about 3 cents per kilowatt hour.

Water can be pumped from a well by releasing compressed air into a discharge pipe lowered into the well. Air bubbles mix with the water, reducing the specific gravity of the column of water sufficiently to lift it to the surface. For best results, the submergence ratio of the air line (percentage of the total length is below water while pumping) should be about 60 percent.

TABLE 11. AVERAGE COST OF SUBMERSIBLE WATER PUMPS, FOUND IN EPA REGION IX, OCTOBER 1974

Head in feet (pumping depth) / Horsepower	60	80	100	120	140	160	180	200	240	280	300	350	400	500	600	700	800	Well Diameter (inches)	Cost ($)
								gallons per hour											
1/3	490	460	430	400	360	340	290	230										6	200
1/2			470	450	480	410	380	340	260	200	110							6	250
3/4					480	470	470	480	380	350	320	270	190					6	300
3/4				750	710	690	640	590	470	400	300							6	300
3/4	1450	1350	1230	1100	940	850	520											6	300
1								470	440	420	400	360	310	210				6	250
1							760	730	660	630	580	500	400	400				6	350
1			1380	1310	1230	1180	1070	920	510	360								6	300
1	2550	2100	1590	900														6	300
1-1/2											480	460	430	370	300	230	150	6	550
1-1/2								780	730	700	680	620	570	430				6	500
1-1/2			1450	1400	1340	1320	1250	1170	1000	900	780							6	450
1-1/2	2880	2640	2380	2100	1740	1560	960											6	450
2												770	730	660	570	460	300	6	600
2								1410	1290	1230	1170	1040	880	390				6	500
2		3000	2800	2610	2400	2290	2010	1620										6	500
3									1440	1410	1380	1310	1230	1060	860	620		6	600
3			3000	2880	2760	2700	2520	2350	1930	1650	1320							6	550

(continued)

TABLE 11 (continued)

Head in ft (pumping depth) / Horse-power	60	80	100	120	140	160	180	200	240	280	300	350	400	500	600	700	800	900	1000	1100	1200	1400	1600	Well Diam-eter (in)	Cost ($)
	gallons per minute																								
5	200																							6	1400
5		180																						6	1400
5		160																						6	1300
5		140	120																					6	1300
5					90	80	80	70																6	1300
5						50	50	50	40	40	40	30	20											6	1800
5							70	60	60	50	40													6	1300
5									50	40	40	40												6	1200
5														20	20	20	20	10						6	1300
5															10	10	10	10	10	10	10			6	1400
7-1/2	300																							8	1600
7-1/2		270	230	180																				8	1700
7-1/2			190	160																				6	1500
7-1/2			170	150	120																			6	1500
7-1/2			140	130	120	110	90																	6	1500
7-1/2						90	90	80	70	70														6	1500
7-1/2								70	60	60	50													6	1600
7-1/2									50	50	50	40												6	1600
7-1/2											40	40	30											6	1700
10			190	170	140																			6	1700
10					180	160	150																	6	1700

(continued)

TABLE 11 (continued)

Head in ft (pumping depth) / Horse-power	60	80	100	120	140	160	180	200	240	280	300	350	400	500	600	700	800	900	1000	1100	1200	1400	1600	Well Diameter (in)	Cost ($)
	gallons per minute																								
10							140	130	120	90	80													6	1700
10										90	90	80	70											6	1700
10											80	70	60	40										6	1800
10													50	50	40									6	1900
15			350	300	230																			8	2000
15					280	270	250	230	190															8	2100
15							200	190	160															6	2100
15									170	150	130													6	2100
15									140	130	130	110	90											6	2100
15												90	80	80										6	2200
15														70	60	50								6	2300
15														60	50	50	40	40						6	2300
15															50	40	40	40	40	30				6	2400
20						340	300	260																8	2600
20						290	280	270	240	210	190													8	2600
20									200	190	180	150												6	2800
20											190	170	150											6	2800
20												140	130	110										6	2700
20														90	80	70	70							6	2700
20															70	70	60	50	40					6	3000
20																	50	50	40	40	40			6	3100

(continued)

TABLE 11 (continued)

Head in ft (pumping depth) / Horse-power	60	80	100	120	140	160	180	200	240	280	300	350	400	500	600	700	800	900	1000	1100	1200	1400	1600	Well Diameter (in)	Cost ($)
	gallons per minute																								
20																		50	40	40	40	30		6	3300
30			570	510	420																			8	3300
30										320	300	240												8	3400
30										260	250	210	180											6	3600
30													190	150										6	3700
30														170	130									6	3700
30														140	130	120	100							6	3700
30																	90	80	80	70	70	50		6	3600
30																		70	70	70	60	50		6	4000
30																			60	50	50	50	40	6	4100
40						550	500	440																8	4400
40												290	280	250	210									8	4700
40													250	200	150									6	4800
40															180	160	140							6	4800
40																140	130	120	110					6	4700
40																			90	90	80	80	70	6	4900
40																					80	70	60	6	5300

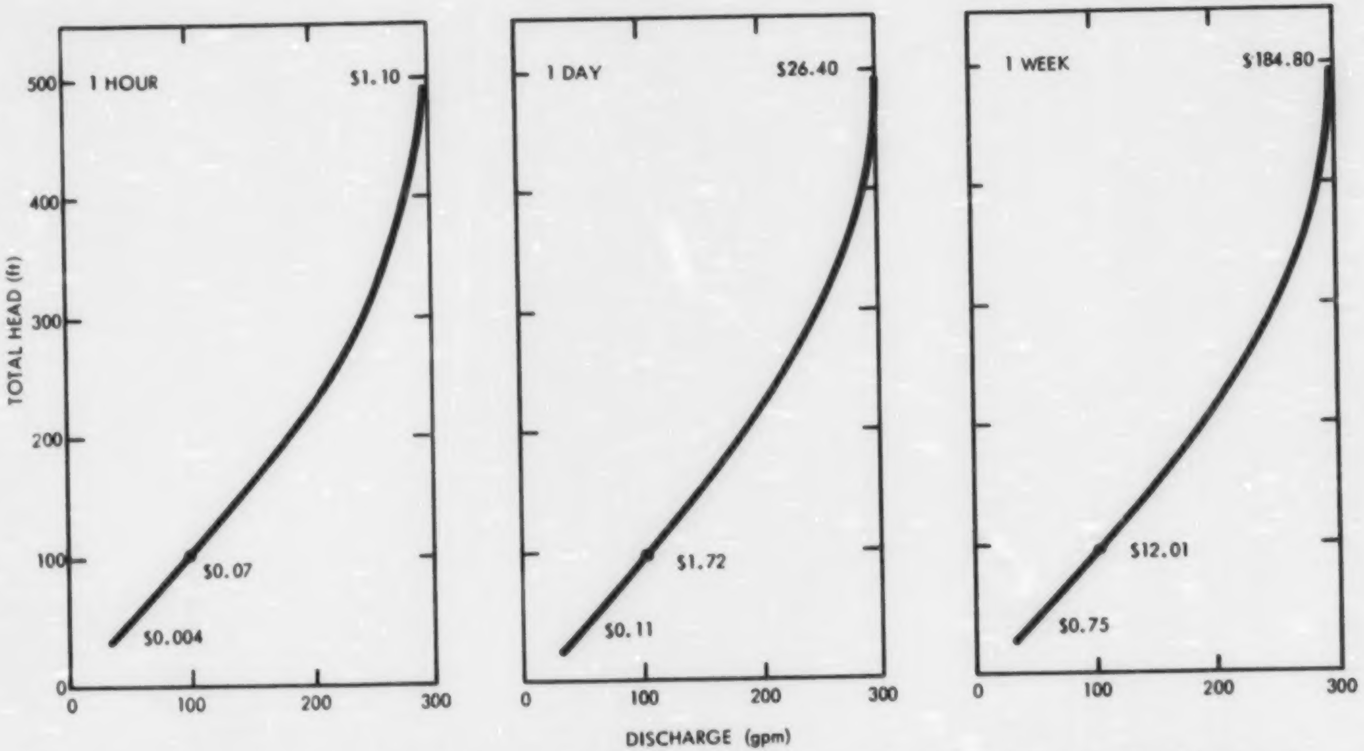

Figure 27. Power costs for continuous pumping of 1 hour, 1 day, 1 week, for specific pumping heads and specific discharge rates, December 1974.

Air-lift pumping can be useful in monitoring wells that need to be pumped only at periodic intervals. Johnson Division UOP (1966) presents data on the relation between total lift, submergence of air line, and water discharged per cubic foot of free air delivered by an air compressor.

Water samples may also be taken by bailing. During cable tool well drilling periodic water samples are retrieved in the bailer and may provide adequate information on the vertical distribution of groundwater quality. Where pumping equipment is not available or where a pump cannot be installed because the diameter of a well is too small, a container such as a weighted bottle or a short section of pipe capped at the bottom can be lowered into the well to collect a sample of water. This sample will give an indication of the chemical quality of water, but should not be used for bacteriological or detailed chemical analysis because of the likelihood of contamination. This method is not recommended except where other methods of sampling are unavailable.

Where it is desired to collect water from a specific depth inside a well, a special cylinder known as a "thief sampler" can be lowered by cable into the well and closed at a predetermined depth. Designs differ, primarily in their closing mechanism. Most types consist of a cylinder that can be less than 2 inches in diameter. A bar with a plunger or cork on each end runs through the cylinder. When the sampler is lowered below the water table to the desired depth and a continuous upward motion is imparted, the two ends close. The most common type of thief sampler is spring loaded. With this type a messenger is lowered along the cable to release the two end cups, which in turn trap the water sample. Many thief samplers are custom made for a specific use. The cost of these samplers is about $100 to $200.

Another method of collecting depth-controlled samples from uncased holes is by installation of mechanical or inflatable packers which temporarily isolate selected water-bearing zones for pumping. This method is of limited value in gravel-packed wells due to vertical movement of groundwater in the gravel pack.

Under special circumstances, continuous monitoring of wells may be necessary. Among the devices used for this purpose are probes designed to measure conductivity, temperature, and selected constituents. These probes may be operated down the well or at the discharge outlet.

Yare (1975) describes a procedure for water sampling during rotary drilling. This technique consists of:

1. Drilling a borehole to the base of a sampling horizon
2. Lowering a wire-wound well screen and riser pipe to the bottom of the borehole and gravel packing the screen

3. Pumping the borehole well until the discharge is clear of drilling fluid

4. Pumping at least 100 gallons of formation water before collecting the sample.

The March-April 1975 issue of Ground Water contains at least six articles dealing with monitor well construction and water sample retrieval. These articles indicate how local conditions can influence the type of monitoring which should be undertaken.

Other Methods of Sampling Groundwater

Tile or ditch drains can provide samples of shallow groundwater. Thomas and Barfield (1974) discuss the limitations of tile effluent for monitoring percolate from soils. The primary limitation for monitoring below the water table is that these samples may represent only the shallowest portion of the aquifer. In some cases this provides very useful information. Springs represent groundwater discharge and can be sampled at the land surface. Interpretation of spring water qualities depends on knowing details of the hydrogeologic framework and groundwater flow patterns. Water sampling of streams under base flow conditions can represent an integration of large groundwater systems and thus be very useful. Proper selection of sampling sites and times requires careful hydrologic judgment.

SECTION V

ANALYSIS OF SAMPLES

INTRODUCTION

Samples, including soil and water, can be taken from the land surface, the vadose zone, or the zone of saturation. In spite of the location of the sample site, many of the sample analysis techniques are similar. A water sample taken at the surface, in the vadose zone, or from the zone of saturation is analyzed in the laboratory using much the same analytical techniques for each parameter. The sample preparation, however, is often quite different.

Soil tests can be divided into physical and chemical analyses. The physical tests are not routinely handled by many chemical analysis laboratories. Agricultural laboratories often provide these services. The physical tests include water content, bulk density or porosity, particle size distribution, soil-moisture characteristic curve, and hydraulic conductivity. The chemical analyses of soil samples include soluble salts, soluble ions, cation exchange capacity and exchangeable ions, and specific surface.

The water tests can be divided into physical, chemical, bacteriological, and radiological analyses. The chemical analyses are further subdivided into inorganic and organic tests. In the discussion of water analysis, consideration is given to sample containers, sample preservation and treatment, and quality control.

CUSTODY CONTROL

The EPA's Office of Water and Hazardous Materials has prepared a procedure (U.S. EPA, 1975) for a recommended "Chain-of-Custody" that will minimize legal complications in obtaining and analyzing water samples. The following comments are abstracted from this document.

Quality assurance should be stressed in all monitoring and in examination of self-monitoring programs no matter what the impetus for the spot check or inspection. The successful implementation of a monitoring program depends to a large degree on the capability to produce valid data and to demonstrate such validity. No other area of environmental monitoring requires more rigorous adherence to the use of validated methodology and quality control measures.

It is imperative that laboratories and field operations involved in the collection of primary evidence prepare written procedures to be followed whenever evidence samples are collected, transferred, stored, analyzed, or destroyed. A primary objective of these procedures is to create an accurate written record which can be used to trace the possession of the sample from the moment of its collection through its introduction into evidence. The procedures described here have been successfully employed and are presented as suggested procedures insofar as they fulfill the legal requirements of the appropriate State legal authority.

Preparation

The evidence-gathering portion of a survey is characterized by the absolute minimum number of samples required to give a fair representation of the effluent or water body sampled. The quantity of samples and sample locations are determined prior to the survey.

Chain-of-custody record tags are prepared prior to the actual survey fieldwork and contain as much information as possible to minimize clerical work by field personnel. The source of each sample is also written on the container itself prior to any field survey work.

Field logsheets used for documenting field procedures and chain-of-custody and to identify samples should be prefilled to the extent practicable to minimize repetitive clerical field entries. Custody during sampling is maintained by the sampler or project leader through the use of the logbook. Any information from previous studies should be copied (or removed) and filed before the book is returned to the field.

Explicit chain-of-custody procedures are followed to maintain the documentation necessary to trace sample possession from the time taken until the evidence is introduced into court. A sample is in your "custody" if:

- It is in your actual physical possession; or
- It is in your view, after being in your physical possession; or
- It was in your physical possession and you locked it in a tamper-proof container or storage area.

All survey participants should receive a copy of the study plan and be knowledgeable of its contents prior to the survey. A presurvey briefing should be held to reappraise all participants of the survey objectives, sample locations and chain-of-custody procedures. After all chain-of-custody samples are collected, a debriefing should be held in the field to check adherence to chain-of-custody procedures and to determine whether additional evidence samples are required.

Sample Collection

1. To the maximum extent achievable, as few people as possible handle the sample.

2. Water samples are obtained using standard field sampling techniques. When using sampling equipment it is assumed that this equipment is in the custody of the entity responsible for collecting the samples.

3. The chain-of-custody record tag is attached to the sample container when the complete sample is collected and contains the following information: Sample number, time taken, date taken, source of sample (to include type of sample and name of firm), preservative, analyses required, name of person taking sample, and witnesses. The front side of the card (which has been prefilled) is signed, timed, and dated by the person sampling. The tags must be legibly filled out in ballpoint (waterproof) ink. Individual sample containers of groups of sample containers are secured using a tamper-proof seal.

4. Blank samples are also taken. Include one sample container without preservative and containers with preservatives from all of which the contents will be analyzed by the laboratory to exclude the possibility of container contamination.

5. The Field Data Record logbook should be maintained to record field measurements and other pertinent information necessary to refresh the sampler's memory if he later takes the stand to testify regarding his actions during the evidence-gathering activity. A separate set of field notebooks should be maintained for each survey and stored in a safe place where they can be protected and accounted for at all times. Standard formats have been established to minimize field entries and include the date, time, survey, type of sample taken, volume of each sample, type of analysis, sample number, preservatives, sample location, and field measurements. Such measurements include temperature, conductivity, dissolved oxygen (DO), pH, flow, and any other pertinent information or observations. The entries are signed by the field sampler. The preparation and conservation of the field logbooks during the survey is usually the responsibility of the survey coordinator. Once the survey is complete, field logs should be retained by the survey coordinator, or his designated representative, as a part of the permanent record.

6. The field sampler is responsible for the care and custody of the samples collected until properly dispatched to the receiving laboratory or turned over to an assigned custodian. He should assure that each container is in his physical possession or in

his view at all times, or is locked in such a place and manner that no one can tamper with it.

7. Colored slides or photographs are often taken which show the outfall sample location and any visible water pollution. Written documentation on the back of the photo should include the signature of the photographer, time, date, and site location. Photographs of this nature, which may be used as evidence, are handled by chain-of-custody procedures to prevent alteration.

In addition to the above recommendations on sample collection, the EPA (U.S. EPA, 1975) provides procedures on transfer of custody and shipment. A section is also included which presents the EPA's National Field Investigation Center's Laboratory Custody Procedures. These procedures should be closely followed, primarily in compliance monitoring.

QUALITY CONTROL

Decisions made using groundwater data are far-reaching. Water quality standards are set to establish satisfactory conditions for a given water use. The laboratory data define whether that condition is being met, and whether the water can be used for its intended purpose. If the laboratory results indicate a violation of the standard, action is required on the part of pollution control authorities. With the present emphasis on legal action and social pressures to abate pollution, the field worker and analyst should be aware of their responsibility to provide results that are a reliable description of the sample. The technician must be aware that his professional competence, the procedures he has used, and the reported values may be used and challenged in court. To satisfactorily meet this challenge, the data must be backed up by an adequate program to document the proper control and application of all of the factors which affect the final result.

Because of the importance of laboratory analyses and the resulting actions which they produce, a program to insure the reliability of the data is essential. It is recognized that all analysts practice quality control to varying degrees, depending somewhat upon their training, professional pride, and awareness of the importance of the work they are doing. However, under the pressure of daily workload, analytical quality control may be easily neglected. Therefore, an established, routine control program applied to every analytical test is necessary in assuring the reliability of the final results.

The need for standardization of methods within a single laboratory is readily apparent. Uniform methods between cooperating laboratories are also important in order to remove the methodology as a variable in comparison or joint use of data between laboratories. Uniformity of methods is particularly important when laboratories are providing data to a common data bank, such as STORET, or when several laboratories are cooperating in joint field surveys. A lack of standardization of methods raises doubts as to the validity of the results reported. If the same constituent is measured by different analytical procedures within a single laboratory, or in several laboratories, the question is raised as to which procedure is superior, and why the superior method is not used throughout.

The physical and chemical methods used should be selected by the following criteria:

- The method should measure the desired constituent with precision and accuracy sufficient to meet the data needs in the presence of the interferences normally encountered in polluted waters
- The procedure should utilize the equipment and skills normally available in the average water pollution control laboratory
- The selected methods should be in use in many laboratories or have been sufficiently tested to establish their validity
- The method should be sufficiently rapid to permit routine use for the examination of large numbers of samples.

The use of EPA methods in all EPA laboratories provides a common base for combined data between Agency programs. Uniformity throughout EPA lends considerable support to the validity of the results reported by the Agency.

Regardless of the analytical method used in the laboratory, the specific methodology should be carefully documented. In some water pollution reports it is customary to state that Standard Methods (APHA, 1971) have been used throughout. Close examination indicates, however, that this is not strictly true. In many laboratories, the standard method has been modified because of recent research or personal preferences of the laboratory staff. In other cases the standard method has been replaced with a better one. Statements concerning the methods used in arriving at laboratory data should be clearly and honestly made. The methods used should be adequately referenced and the procedures applied exactly as directed.

Knowing the specific method which has been used, the reviewer can apply the associated precision and accuracy of the method when interpreting the laboratory results. If the analytical methodology is in doubt, the data user may honestly inquire as to the reliability of the result he is to interpret.

In field operations, the problem of transport of samples to the laboratory, or the need to examine a large number of samples to arrive at gross values will sometimes require the use of rapid field methods. Such methods should be used with caution, and with a clear understanding that the results obtained may not compare in reliability with those obtained using standard laboratory methods. The data user is entitled to know that approximate values may have been obtained for screening purposes only, and that the results may not represent the customary precision and accuracy obtained in the laboratory.

SOIL

Physical Analyses

WATER CONTENT. The water content of field samples is commonly obtained by gravimetry with oven drying (Gardner, 1965). The sample is placed in a drying oven at about 105°C. The difference in mass before and after drying represents the water content on a dry mass basis. (Gardner also describes a field method for determining water content using gravimetry with drying by burning alcohol.)

The cost of a soil-moisture drying oven varies between \$300 and \$450. The cost of conducting a water content analysis varies from about \$4 to \$6 per sample. Figure 28 gives the cost of multiple water content determinations including a discount rate.

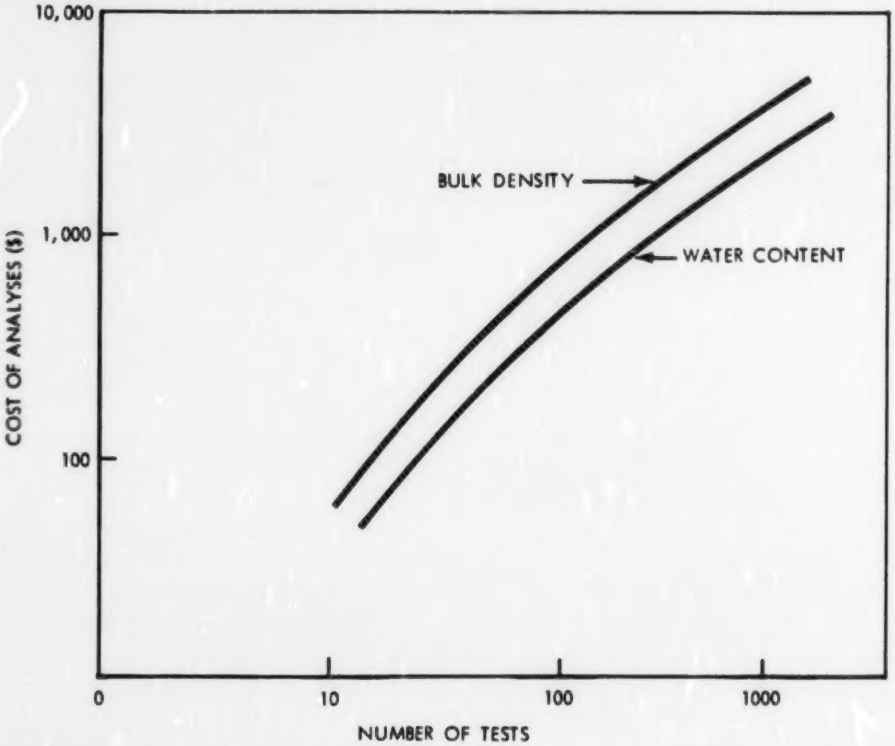

Figure 28. Costs for determinations of water content and bulk density in soils, September 1974.

BULK DENSITY AND POROSITY. Bulk density is used to calculate soil porosity. Also, together with water content data, bulk density may be used to estimate the amount of water to bring the soil to saturation. Soil cores obtained in the field are oven dried at 105°C until constant weight is attained. The bulk density of the sample is the oven-dry mass divided by the volume. Blake (1965) presents alternative methods to calculate bulk density, including determination in place by filling the soil cavity with a measured volume of sand. Blake also discusses a double-probe technique for measuring bulk density in situ via gamma radiation.

The cost of a bulk density determination is around $6 to $10 per sample; however, discount rates may be quite high for these determinations. The cost of multiple bulk density tests including a discount rate is given in Figure 28.

PARTICLE-SIZE DISTRIBUTION. Information on particle-size distribution of drilling samples provides explicit data on the vertical distribution of gravels, sands, silts, and clays. Such data may subsequently be related to gamma logs. According to Day (1965) fractionation and particle-size analyses mainly involve sieving and sedimentation procedures.

Sieving is used to separate particles coarser than 0.05 mm. In practice, a sample is prepared in standard fashion and passed through a net of sieves with openings graded to permit separation of various particle sizes. Either wet sieving or dry sieving is used.

Sedimentation is used principally to determine the percentage of clay in a sample. This fraction is highly active in ion exchange and adsorption. The presence of layers with high clay levels tends to cause lower relative permeability. Sedimentation is accomplished by either the pipette or hydrometer method. Results are usually presented on a curve which plots the percentage of particles, by weight, smaller than a given size, versus the logarithm of the particle size.

The basic equipment used in particle size analysis is a set of sieves and a sieve shaker. Each sieve costs about $12 to $16. A full set of U.S. Standard or Tyler series can cost as much as $225. However, reduced numbers of sieves can be used for soil particle size analysis. The USDA-recommended set of soil sieves costs about $60. The average cost of a mechanical shaker is about $300. Under specialized conditions it may be necessary to determine the sedimentation fraction that passes through even the finest sieves.

The cost of a particle size analysis can vary depending upon the particle size range of interest. The average cost of an analysis of gravel through the clay sizes is $25; the cost of an analysis is $40 if less than a 25-gram sample is available. The normal particle size analysis calls for a sand and gravel determination and this costs about $8 to $10. If an analysis of clay sizes only is required, the cost is about $20 per sample. Volume discount rates may be important in the costs of these tests.

SOIL-WATER CHARACTERISTIC CURVE. A knowledge of the water content versus pressure relationships of a soil is essential in calculating hydraulic conductivity and the rate of soil-water movement. A soil-water characteristic curve is needed to transform water content data from neutron logging into equivalent soil pressures.

The modified Haines method may be used to obtain the soil-water characteristic curve up to suctions of about 1 atmosphere. This method employs the equipment shown in Figure 29. Soil cores are carefully placed on the fritted glass plate and saturated (Nielsen et al., 1973). Excess water is removed and the hanging water column is adjusted through a desired range of negative pressure. A plot of water content versus soil pressure during a drying cycle, which occurs during the Haines method, is usually different from the curve during wetting, as evidenced in Figure 30. This hysteresis phenomenon must be kept in mind during interpretation of field data. Since the fritted glass membrane usually fails at about 0.8 atmosphere negative pressure, other methods are required to obtain the water content versus soil pressure relationship for greater suction. Klute (1965) describes one such method (the pressure-membrane method) which involves applying air pressure to a soil sample in a weighable cell.

Estimates on the water content of a soil at field capacity may be obtained by the so-called one-third atmosphere technique (Peters, 1965). Alternatively, field capacity can be estimated in situ. A square plot of about 3 meters per side is prepared with a raised border to permit ponding. Water is applied until the desired soil depth is wetted. After recession of the water, the soil surface is covered with polyethylene sheeting to prevent evaporation. After allowing about 2 days for drainage, soil samples are obtained for gravimetric determination of water content. Incidentally, the test pond also can be used to estimate infiltration rates into the soil.

The cost of developing a soil-water characteristic curve is a function of the number of tests to be run. These tests are not routinely run in many laboratories. The average cost of developing a soil-water characteristic is about $30 to $40 per sample. Discounts of over 30 percent can be expected for large numbers of samples. A series of 100 tests, for example, would cost about $2000.

HYDRAULIC CONDUCTIVITY. Core samples obtained from the field may be used to evaluate both the saturated and unsaturated hydraulic conductivity for the soil depth sampled. For the saturated case a permeameter may be used in which a constant positive head is applied to a soil sample, the discharge rate is measured, and the hydraulic conductivity is calculated.

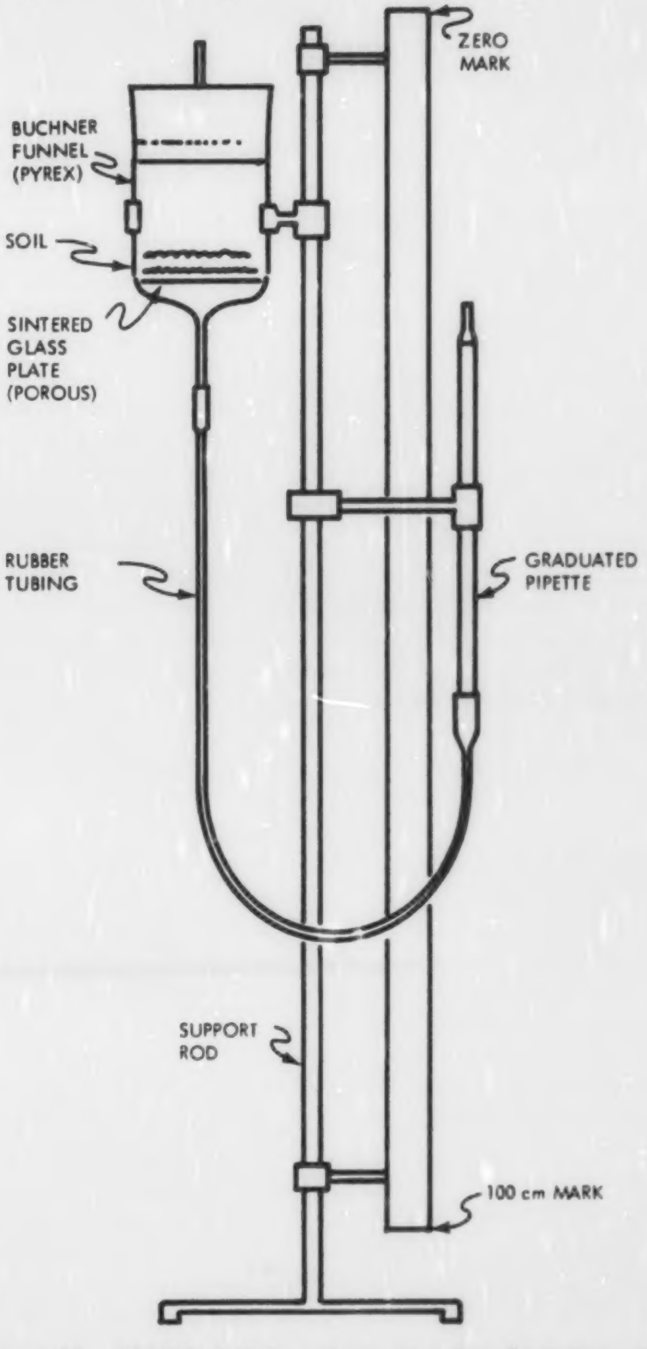
ZERO MARK
BUCHNER FUNNEL (PYREX)
SOIL
SINTERED GLASS PLATE (POROUS)
RUBBER TUBING
GRADUATED PIPETTE
SUPPORT ROD
100 cm MARK

Figure 29. Modified Haines Apparatus for obtaining soil-water characteristic curves (after Day et al., 1967).

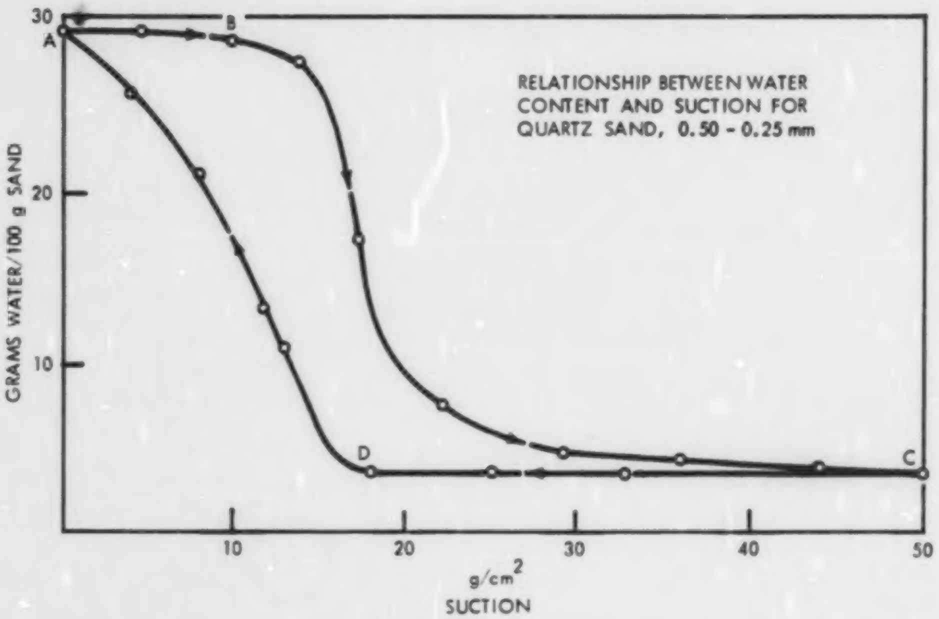

Figure 30. Soil-water characteristic curve, showing hysteresis. ABC = drying, CDA = wetting (after Day et al., 1967).

SPECIFIC SURFACE. The cation exchange capacity and specific surface together govern the sorption characteristics of a soil. Unfortunately, the mechanisms for adsorptions directly onto the surface of soil colloids are imperfectly understood.

Mortland and Kemper (1965) discuss the principles of adsorption, relating to the specific surface of clays. In addition, a method for determining specific surface based on sorption of ethylene glycol is presented. Specific surface determinations are not routinely done and require a specific cost quote.

In addition to the chemical analyses, further soil testing can include a clay mineral identification that costs about $30 per sample. A simple mineral identification costs about $5 while a mineral separation and identification can cost $25. A trace element determination such as zinc, manganese, iron, or copper costs about $5.

The costs of soil-water chemical tests are approximately the same as the costs of water sampling tests.

The range of tests that are performed in a hydrologic laboratory is varied and usually quite unfamiliar to the field technician. For this reason an example test schedule and cost quote is provided in Table 12.

TABLE 12. HYDROLOGIC LABORATORY TESTS AND COST SCHEDULE, SEPTEMBER 1974

Hydrologic laboratory tests	Soil analyses costs ($)
Dry Unit Weight	6.00
Electrical Resistivity	20.00
Formation Factor (includes determination of conductivity of interstitial water)	25.00
Hydraulic Conductivity	
Saturation flow, undisturbed samples in standard cylinders at effective stresses < 90 psi; tested with formation water	
Vertical flow	30.00
Horizontal flow	35.00
Nonstandard undisturbed samples, vertical or horizontal flow	40.00
Saturated flow, undisturbed samples at simulated overburden loads to 5000 psi and pore pressures to 3000 psi, vertical or horizontal flow; tested with formation water	40.00
Unsaturated flow, undisturbed samples (determination of unsaturated hydraulic conductivity as a function of moisture content over a range of negative heads to −2 atmospheres)	75.00
Moisture Content (as received)	6.00
Moisture-Tension Curve (water content as a function of negative head, by the pressure-plate method)	40.00
Particle-Size Analysis	
Complete (gravel through clay sizes)	25.00
Complete, if < 25-gram sample available	40.00
Sand and gravel sizes only	10.00
Clay sizes only (centrifuge method)	20.00
Permeability; single-phase flow of gas or liquid other than water; undisturbed samples	40.00
Pore-Water Extraction — centrifuge, immiscible displacement, or high-pressure (20,000 psi) squeeze methods	40.00
Porosity and "Specific Yield"	
Total porosity (gravimetric method: includes granular specific gravity and dry unit weight)	12.00
Pore-size distribution curve—cohesive samples	
Mercury injection method: includes simulated moisture-tension curve, approximate "specific yield," effective porosity at 2000 psi Hg pressure, total porosity, specific gravity, dry unit weight	35.00
Pore-size distribution curve — friable samples	
Moisture-tension method, see above: includes "specific yield," effective porosity at 2 atmospheres moisture tension, total porosity, specific gravity, dry unit weight	50.00
"Specific Yield" (not including porosity)	
Direct determination, using moisture-tension curve	40.00
Indirect methods	
Centrifuge moisture equivalent (suitable for sands only)	25.00
Mercury-injection method, cohesive samples only (injected porosities at 30 to 50 psi typically correspond to the approximate range of "specific yield"	20.00
Thermal Conductivity	25.00
Specific Gravity (grain density)	8.00
Sample preparation and equipment modification for above tests, if required by unusual sample conditions or test requirements	8.00/hr.

Unsaturated hydraulic conductivity may also be measured in the laboratory using, for example, the steady-state method of Klute (1965). Soil is placed in a cell containing a porous plate and two tensiometers. After saturating the soil, air pressure is applied, the discharge rate of water leaving the soil is measured, and the tensiometers are read. The hydraulic conductivity at the equivalent negative pressure is calculated from Darcy's equation. With this method a curve may be plotted depicting the relationship between conductivity and negative pressure head. Using a soil-water characteristic curve, the conductivity-pressure relationship may also be obtained.

Special equipment is required to conduct a hydraulic conductivity test in the saturated state. The cost can vary with the effective stress required from $30 to $50 for each test. These tests are also subject to large discount rates. The expected cost for 100 tests is about $2400.

Chemical Analysis

SOLUBLE IONS. Soluble salts refer to the soil constituents of an inorganic nature that are appreciably soluble in water. The following steps are usually taken in an analysis for soluble salts: (1) preparing a sample by bringing the soil-water content to some prescribed value; (2) extracting the sample; and (3) measuring or analyzing the salt content of the extract.

The soil-water content at which the salt is extracted is a matter of concern. The saturation extract, for example, is a technique used by agriculturists to relate soluble salts to field moisture range. A problem with diluting the sample, as done by the saturation extract, is that while the concentration of some ions decreases on dilution, the concentration of others may increase (Reitemeier, 1946). For example, as water is added to the soil, precipitated calcium carbonate or gypsum may gradually dissolve, releasing calcium and possibly magnesium ions into solution. Concurrently, the additional concentrations of calcium and magnesium may displace sodium on the exchange complex, thereby increasing the sodium level in the soil solution. Overall, calcium, magnesium, and sodium may increase in the soil solution. In contrast, chloride and nitrate may decrease in concentration because of dilution and negative adsorption. Reitemeier (1946) recommended that for arid land soils, dissolved ions should be determined at or near the water content at which the results are to be applied. Consequently, the soil solutes of samples from deeper horizons of the vadose zone should be extracted at the prevailing soil-water pressure.

Pressure membrane apparatus may be used to extract soil solution samples in the dry range (Richards, 1954). Thus, if a soil-water characteristic is available for the sample, together with gravimetric water content data, the equivalent soil-water pressure can be determined. This pressure is then applied to the soil sample in the membrane. A problem with this technique is that solution is extracted from the larger pores which may not have the same chemical composition as that in the smaller interstices (Rhoades and Bernstein, 1971).

A soil moisture extractor that uses the pressure membrane technique costs about $400. These units, however, require a compressor that costs about $650 and an independent pressure control manifold that costs from $400 to $800 depending upon the number of outlets required.

For surface soils other factors should be examined in the determination of soluble salts. For irrigated soils or land disposal operations subject to wetting and drying, the water content of soils may range over large values because of evaporation, so that conversion to the field water content value may not be meaningful (Pratt, 1972). In this case, the saturation extract technique is recommended (Rhoades and Bernstein, 1971). Water content by this method represents about twice that at field capacity; therefore, the salt content extracted from the saturated sample is about one-half the concentration at field capacity. Bower and Wilcox (1965) explain in detail the procedure to obtain a saturated extract.

If detailed information is required on specific ionic constituents, chemical analyses using procedures presented in "Methods of Soil Analysis" (Black, 1969) may be used. The principal ions of importance in most soil studies are: calcium (Ca^{++}), magnesium (Mg^{++}), potassium (K^+), sodium (Na^+), carbonate ($CO_3^=$), bicarbonate (HCO_3^-), sulfate ($SO_4^=$), chloride (Cl^-), and boron, as well as the nitrogen series of ions. For soluble ions, the procedures given in the water analyses section are applicable.

The cost of an electrical conductivity test on a soil sample is about $5 to $6. The cost of conducting 10, 100, and 1000 tests is about $60, $500, and $4000, respectively. The cost of determining soluble cations such as sodium, potassium, calcium, and magnesium, is about $3 for each chemical parameter tested. To obtain the pH of soil a saturation extract costs about $2 to $3.

CATION EXCHANGE CAPACITY. Methods for determining the sum of individual exchangeable ions of a sample are given in Black (1969). This sum is equal to the cation exchange capacity (CEC). Alternatively, the CEC may be obtained directly using methods detailed by Chapman (1965). Briefly, the exchangeable cations in a soil sample are replaced by either ammonium acetate or sodium acetate, and the amounts of ammonium and sodium ions adsorbed are determined. A problem may develop with the use of ammonium ions because this ion becomes strongly adsorbed on some clays. Cation exchange capacity is expressed as milliequivalents (meq) per 100 grams of sample.

The cost of determining the total cation exchange capacity is about $11. The cost of determining the sodium, potassium, magnesium, and calcium exchangeable cations is about $12. The cost of conducting a base exchange analysis which includes pH of saturated soil paste; electrical conductivity; boron in soil extract; total cation exchange capacity; exchangeable percent of exchange capacity for calcium, magnesium, potassium and sodium; limestone content; calcium requirement; nitrates; bicarbonate exchangeable phosphorous; and exchangeable potassium; is about $20 per sample.

WATER

In addition to water sampling techniques and field determinations, the sample containers, preservation technique, and method of analysis are key factors in monitoring groundwater quality. The U.S. Environmental Protection Agency has published Manual of Methods for Chemical Analysis of Water and Wastes (1974a) and Methods for Organic Pesticides in Water and Wastewater (1971). The U.S. Geological Survey has published Methods of Collection and Analysis of Water Samples (Rainwater and Thatcher, 1960) and is currently updating and expanding this coverage through its series on Techniques of Water Resources Investigations, Book 5, Laboratory Analysis (Barnett and Mallory, 1971; U.S. Geological Survey, 1973).

The American Public Health Association (1971) has published the 13th Edition of Standard Methods for the Examination of Water and Wastewater. The major portions treating groundwater pollution monitoring are: Part 100 — "Physical and Chemical Examination of Natural and Treated Waters in the Absence of Gross Pollution"; Part 200 — "Physical, Chemical, and Bioassay Examination of Polluted Waters, Wastewaters, Effluents, Bottom Sediments, and Sludges"; Part 300 — "Examination of Water and Wastewater for Radioactivity"; and Part 400 — "Bacteriological Examination of Water to Determine its Sanitary Quality".

Water testing laboratories can be found at Federal, State, county, and municipal levels. Universities and private companies also provide analysis capabilities. The cost of each analysis varies greatly with the degree of automation, the number and kinds of tests required, and the accuracy of the tests. The Corps of Engineers, the EPA, and other agencies require a certain sensitivity for the tests performed. The costs increase with the sensitivity of the analysis. The costs presented in this section for water-quality analysis represent an average cost for commercial laboratory services. The costs do not include a sample preparation fee, which can vary from $3 to $25. Most commercial laboratories allow a 10 percent discount for invoices over $500 per month and a 20 percent discount for invoices of $1000 per month or more. In laboratory selection, factors such as location relative to the sampling area, time to complete analyses, and quality assurance programs must be considered. In cost of analysis determinations, special considerations should be given for group rates such as the following October 1974 values:

Major Inorganic Chemicals

Group Rate $12

Calcium
Magnesium
Sodium
Potassium
Carbonate
Bicarbonate
Sulfate
Chloride
Nitrate
Total dissolved solids
pH
Electrical conductivity

Other Inorganic Chemicals

Group Rate $40

Silica
Boron
Fluoride
Nitrogen forms
Phosphorous forms
Hardness

Drinking Water Trace Elements

Group Rate $50

Iron
Manganese
Arsenic
Barium
Cadmium
Hexavalent chromium
Copper
Cyanide
Lead
Selenium
Silver
Zinc

Other Trace Elements

Group Rate $55

Vanadium
Molybdenum
Bromide
Iodide
Nickel
Aluminum
Cobalt
Lithium
Sulfide
Beryllium

Gases

Group Rate $30

Methane
Hydrogen sulfide
Carbon dioxide
Dissolved oxygen
Residual chlorine

Insecticides

Group Rate $32

Alopin
Chlordane
DDD
DDE
DDT
Dieldrin
Endrin
Heptachlor
Heptachlor Epoxide
Lindane
Toxaphene

Herbicides

Group Rate $45

2,4-D
2,4,5-T
Silvex

Radiochemical

Group Rate $100

Gross Alpha, Beta dissolved and suspended
Radium-226 by Radon
Uranium Fluorometric

Determinations

The major constituents of water with respect to groundwater pollution may be grouped into the following physical, inorganic chemical, organic chemical, bacteriological, and radiological classifications:

Physical

- Temperature
- Density
- Odor
- Turbidity
- Color

Inorganic Chemical

- Major constituents
- Other constituents
- Trace elements
- Gases

Organical Chemical

- Carbon
- Biochemical oxygen demand
- Methylene blue active substances
- Nitrogen
- Chemical oxygen demand
- Phenolic materials
- Insecticides and herbicides

Bacteriological

- Coliform group
- Pathogenic microorganisms
- Enteric viruses

Radiological

- Gross alpha activity
- Gross beta activity
- Strontium
- Radium
- Tritium

Significant removals of the organic chemical, bacteriological, and radiological constituents of percolated wastes ordinarily occur in the topsoil and vadose zone.

Physical

Measurements of water temperature and notes concerning odor are often made at the sampling point. Density and turbidity determinations are applicable only in special situations. Density is important in the case of disposal of fluids of high density compared to native groundwater, and turbidity is important in well disposal or injection programs.

The cost of a density determination is about $5, and the cost of a turbidity test is about $6. The cost of odor and color determinations are about $1 to $5, respectively.

Inorganic Chemical

The primary divisions of inorganic chemical constituents with respect to groundwater pollution are the following:

1. Major — the major constituents of groundwater
2. Other — other common constituents of importance in water use and waste disposal
3. Drinking Water Trace — trace constituents of concern for drinking water quality
4. Other Trace — trace constituents of concern in waste disposal
5. Gases — common gases in groundwater and in, or generated by, wastes.

The constituents within these divisions are:

Major

Calcium
Magnesium
Sodium
Potassium
Carbonate
Bicarbonate
Sulfate
Chloride
Nitrate
Total dissolved solids
pH
Electrical conductivity

Other

Silica
Boron
Fluoride
Nitrogen forms
Phosphorus forms
Hardness

Drinking Water Trace

Iron
Manganese
Arsenic
Barium
Cadmium
Hexavalent chromium
Copper
Cyanide
Lead
Selenium
Silver
Zinc
Mercury

Other Trace

Vanadium
Molybdenum
Bromide
Iodide
Nickel
Aluminum
Cobalt
Lithium
Sulfide
Beryllium

Gases

Methane	Carbon dioxide
Hydrogen sulfide	Dissolved oxygen
Residual chlorine	

The procedures for sample collection, treatment, and analytical determination vary widely from wastewaters and effluents to relatively unpolluted or natural groundwaters. This basic difference is recognized in APHA's Standard Methods (1971), wherein a major subdivision occurs between natural waters and polluted waters. These differences arise because of factors such as interference effects and biologic activity. In general, wastewaters, particularly those of industrial origin, may often require specialized sample collection and analytical procedures.

CONTAINERS. Factors that are pertinent in selecting containers for collecting and storing water samples are resistance to solution and breakage, efficiency of closure, size, shape, weight, availability, and cost. Hard rubber, polyethylene, teflon, and other types of plastics, and some types of borosilicate glass are suitable based on experience within the U.S. Geological Survey and other agencies. Glass bottles may be a problem for analysis of boron, silica, sodium, and hardness. For dissolved oxygen determinations, only glass containers should be used. For silica determinations, only plastic containers should be used.

Before use, all new bottles should be thoroughly cleansed, filled with water, and allowed to soak several days. The soaking removes much of the water-soluble material from the container surface. The source of the sample and conditions under which it was collected should be recorded immediately after collection. In the case of wells, this should include pumping rate, duration of pumping if known, water level, temperature of water, and electrical conductivity. Samples from wells near pollution sources should be accompanied by a description of local conditions, such as "percolation pond empty."

Narrow-mouth 250-ml polyethylene bottles cost about 30 to 40 cents each. The cost of a comparable size glass bottle is about 20 to 30 cents. If the bottles are purchased by the case, the discount rate is about 10 percent for 1 to 4 cases, 15 percent for 5 to 19 cases, and 20 percent for 20 or more cases. Shipping sleeves for use with plastic bottles cost about $18 per 100 sleeves. Glass mailers cost about $35 for a carton of 75.

PRESERVATION OF WATER AND WASTE SAMPLES. EPA's Manual of Methods for Chemical Analysis of Water and Wastes (U.S. EPA 1974a) is a basic reference for monitoring water and wastes in compliance with the requirements of the Federal Water Pollution Control Act Amendments of 1972. Included is a detailed discussion of sample preservation techniques.

Preservation techniques can only retard the chemical and biological changes that inevitably continue after the sample is taken in the field. Certain changes occur in the chemical structure of the constituents that are a function of physical conditions. Metal cations may precipitate as hydroxides or form complexes with other constituents, cations or anions may change valence states under certain reducing or oxidizing conditions, and other constituents may dissolve or volatilize with the passage of time. Metal cations may also adsorb onto surfaces (glass, plastic, quartz, etc.). Biological changes taking place in a sample may change the valence of an element. Soluble constituents may be converted to organically bound materials, or cellular material may be released into solution.

Methods of preservation are relatively limited and are intended generally to (1) retard biological action, (2) retard hydrolysis of chemical compounds and complexes, and (3) reduce volatility of constituents. Preservation methods are generally limited to pH control, chemical addition, refrigeration, and freezing. Refrigeration at temperatures near freezing or below is the best preservation technique available, but it is not applicable to all types of samples. The preservative measures recommended by the EPA (U.S. EPA, 1974a) are given in Table 13. When the dissolved concentration is to be determined, the sample is filtered immediately after collection through a 0.45-micron membrane filter and the filtrate is analyzed by the specified procedure. Specific techniques for monitoring wastewater are given in the EPA's Handbook for Monitoring Industrial Wastewater (U.S. EPA, 1973), and American Public Health Association (1971), Part 200.

SAMPLE COLLECTION AND TREATMENT FOR GROUNDWATERS. Brown et al. (1970) present data that are applicable to groundwater sampling. An analysis will more closely represent the water at the time of collection if separate samples are taken for determination of certain groups of ions. The test procedure should determine whether a given analytical determination should be performed on a settled, filtered, or well-mixed sample.

On-site determinations are mandatory for temperature, pH, dissolved oxygen, and specific conductance. For laboratory determinations the following procedures are recommended by Brown et al.:

> One sample of about 1 liter volume should be collected and immediately filtered through a 0.45-micron membrane filter. The following determinations are made on the filtrate: boron, chloride, fluoride, lithium, nitrate, nitrite, dissolved solids, dissolved phosphorous, potassium, selenium, silica, sodium, and sulfate.
>
> A second sample of about 2 liters should be collected and immediately filtered through a 0.45-micron membrane filter. The filtrate should be acidified with double-distilled, reagent-grade nitric acid to a pH of 3 or less. The following determinations

TABLE 13. RECOMMENDED SAMPLING AND PRESERVATION TECHNIQUES FOR INORGANIC CHEMICAL DETERMINATIONS

Measurement	Volume (ml)	Preservative	Holding time
Arsenic	100	HNO_3 to $pH<2$	6 months
Bromide	100	Cool to 4°C	24 hours
Chloride	50	None required	7 days
Cyanide	500	Cool to 4°C NaOH to pH 12	24 hours
Dissolved oxygen	300	On-site determ.	none
Fluoride	300	Cool to 4°C	7 days
Hardness	100	Cool to 4°C	7 days
Iodide	100	Cool to 4°C	24 hours
Metals, dissolved	200	Filter on site HNO_3 to $pH<2$	6 months
Metals, total	100	HNO_3 to $pH<2$	6 months
Mercury, dissolved	100	Filter HNO_3 to $pH<2$	38 days (glass) 13 days (hard plastic)
Mercury, total	100	HNO_3 to $pH<2$	38 days (glass) 13 days (hard plastic)
Ammonia nitrogen	400	Cool to 4°C H_2SO_4 to $pH<2$	24 hours
Nitrate nitrogen	100	Cool to 4°C H_2SO_4 to $pH<2$	24 hours
Nitrite nitrogen	50	Cool to 4°C	24 hours
pH	25	Cool to 4°C On-site determ.	6 hours
Dissolved orthophosphate	50	Filter on site Cool to 4°C	24 hours
Hydrolyzable phosphorus	50	Cool to 4°C H_2SO_4 to $pH<2$	24 hours
Total phosphorus	50	Cool to 4°C	24 hours

(continued)

TABLE 13 (continued)

Measurement	Volume (ml)	Preservative	Holding time
Total dissolved phosphorus	50	Filter on site Cool to 4°C	24 hours
Filterable residue	100	Cool to 4°C	7 days
Non-filterable residue	100	Cool to 4°C	7 days
Total residue	100	Cool to 4°C	7 days
Volatile residue	100	Cool to 4°C	7 days
Selenium	50	HNO_3 to $pH<2$	6 months
Silica	50	Cool to 4°C	7 days
Specific conductance	100	Cool to 4°C	24 hours
Sulfate	50	Cool to 4°C	7 days
Sulfide	50	2 ml zinc acetate	24 hours
Sulfite	50	Cool to 4°C	24 hours

are made on the acidified filtrate: aluminum, arsenic, barium, cadmium, calcium, chromium, cobalt, copper, iron, lead, lithium, magnesium, manganese, molybdenum, nickel, potassium, silver, sodium, strontium, vanadium, and zinc.

A third sample of about 1 liter should be collected and not filtered. The following determinations may be made on this sample: ammonia, organic nitrogen, chemical oxygen demand, cyanide, phosphorus, and turbidity.

Collection of additional samples and individual treatment may be necessary for the nitrogen forms, cyanide, dissolved oxygen, organic phosphorus, and sulfide.

SELECTION OF SPECIFIC DETERMINATIONS. The major cations and anions should usually be determined in a water analysis, along with pH, electrical conductivity, and total dissolved solids at 25°C. The major cations are Ca^{++}, Mg^{++}, Na^{+}, and K^{+}. In areas of polluted groundwater, ammonium ion (NH_4^+) may also be a significant cation. The major anions are $CO_3^{=}$, HCO_3^-, Cl^-, $SO_4^{=}$, and possibly NO_3^-. Another significant anion may be fluoride (F^-). If the major constituents are determined, then the cation-anion balance in equivalents can be checked. Similarly, the calculated total dissolved solids can be compared with the residue. Silicate (SiO_2) is an undissociated form found in many groundwaters that should be determined prior to calculation of total dissolved solids. The electrical conductivity at 25°C can be compared to the total dissolved solids. The chemical analysis can thus be checked several ways for internal consistency. The determination of major ions also permits interpretation by the use of trilinear diagrams as well as the application of physical chemistry to groundwater quality problems. The cost of analyses of inorganic chemicals in water is given in Table 14. Although costs for dissolved chemicals are of primary interest in groundwater studies, the cost of analysis which includes suspended chemicals (total) are also given for surface waste-water studies.

Specific uses dictate the items of interest in water supply monitoring. In agricultural areas where irrigation water is pumped from groundwater, boron is analyzed and sodium adsorption ratio and residual bicarbonate are calculated from the analysis of major constituents. In municipal areas using groundwater, fluoride, iron, and manganese, as well as selected trace metals such as arsenic, are analyzed. Hardness is calculated. Many trace metals occur in insignificant concentrations in groundwater and with careful judgment can often be eliminated from the chemical analysis.

In monitoring near waste disposal sites, consideration should be given to constituents in the wastewater or percolate. Judgment based on soil chemistry and geochemistry can then be used to predict what constituents should be analyzed. Other forms of specific constituents may be important, such as hydrogen sulfide (H_2S) and nitrite ion (NO_2^-). Past groundwater quality studies have often reflected a lack of sampling for constituents other than those of interest. It should be remembered that other constituents can often yield significant data. Also, no ion moves by itself; that is, a percolating nitrate ion must be accompanied by some cation, for example. Similarly, thermodynamic or kinetic studies of groundwater quality require knowledge of concentrations of the major constituents, as well as pH and oxidation potential. However, in some cases judgment can be used to effectively utilize partial chemical analyses. In salt-balance studies in irrigated areas, for example, electrical conductivity alone sometimes can be used quite effectively.

Organic Chemical

Goerlitz and Brown (1972) discuss methods for analysis of organic substances in water. Before a proper sampling program for organic substances can be initiated, the nature of the organic compounds must be considered. Organic matter in a body of water may be distributed on the surface, in suspension, adsorbed on suspended sediment, in bed materials, and in solution. Because of this wide and generally unpredictable distribution of organic material in a body of surface water, the collection of representative samples requires care and often the use of specialized sampling equipment. In most cases, samples for organic analysis are best collected with the same equipment and technique used for the collection of samples for suspended-sediment measurements (Guy and Norman, 1970). Most surface water

TABLE 14. COSTS OF INORGANIC CHEMICAL DETERMINATIONS FOR GROUNDWATER POLLUTION,[a] OCTOBER 1974

Major parameters (mg/ℓ)	Water analysis cost ($)		
	0.x	0.0x	0.00x
Calcium dissolved	5		
Calcium total	10	12	
Magnesium dissolved	5		
Magnesium total	5	10	20
Sodium dissolved	5		
Sodium total	5	7	10
Potassium dissolved	5		
Potassium total	8	10	15
Carbonate	10		
Bicarbonate	5		
Sulfate	5		
Chloride	5		
Nitrate	2	5	
Dissolved solids, fixed	5		
Dissolved solids, total	1		
Dissolved solids, volatile	5		
pH	3		
Electrical conductivity	3		
Others (mg/ℓ)			
Silica	5	10	15
Boron dissolved	10		
Boron total	15	17	20
Fluoride dissolved	10		
Fluoride total	15	20	
Nitrogen dissolved KJD	10		
Nitrogen NH_4 as N total	5		
Nitrogen NH_4 as N dissolved	5		
Nitrogen NO_2 as N dissolved	5		
Nitrogen NO_2 as N total	5	8	
Nitrogen NO_3 as N dissolved	5	8	
$NO_2 + NO_3$ as N dissolved	5		
$NO_2 + NO_3$ as N total	5		
Nitrogen total KJD as N	10	11	
Phosphate dissolved Ortho as PO_4	3	5	
Phosphate Ortho dissolved as P	3		
Phosphate Ortho total as P	3	5	
Phosphate dissolved as P	5		
Phosphate total HYD as P	10		

(continued)

TABLE 14 (continued)

Others (mg/ℓ)	Water analysis cost ($)		
	0.x	0.0x	0.00x
Phosphate total as P	10		
Hardness, calcium	3		
Hardness, carbonate	3		
Hardness, magnesium	3		
Hardness, non-carbonate	1		
Hardness, total	3		
Drinking water trace (mg/ℓ)			
Iron	5		
Iron dissolved	5		
Iron +2 and +3	5		
Iron ferrous	5		
Iron total	10	12	15
Manganese	5		
Manganese dissolved	5		
Manganese total	5	7	10
Arsenic dissolved	10		
Arsenic total	15	17	20
Boron dissolved	10		
Boron total	10	12	15
Cadmium dissolved	10		
Cadmium total	10	12	15
Chromium dissolved	8		
Chromium hexavalent	8	9	10
Chromium total	8	9	10
Copper dissolved	5		
Copper total	5	7	10
Cyanide	10	15	
Lead dissolved	10		
Lead total	13	14	15
Selenium dissolved	15		
Selenium total	15	17	20
Silver dissolved	10		
Silver total	10	12	15
Lime dissolved	5		
Lime total	10	12	15
Mercury dissolved	10		
Mercury total	10	12	15

(continued)

TABLE 14 (continued)

Other traces (mg/ℓ)	Water analysis cost ($)		
	o.x	o.ox	o.oox
Vanadium dissolved	10		
Vanadium total	10	15	20
Molybdenum dissolved	10		
Molybdenum total	10	12	15
Bromine	10	15	
Iodine	10	15	
Nickel dissolved	10		
Nickel total	10	12	15
Aluminum dissolved	10		
Aluminum total	10	15	20
Cobalt dissolved	10		
Cobalt total	10	12	15
Lithium dissolved	12		
Lithium total	12	14	15
Sulfide dissolved	5		
Sulfide total	5		
Beryllium dissolved	10		
Beryllium total	10	12	15
Gases (mg/ℓ)			
Hydrogen sulfide	5	7	
Carbon dioxide	5		
Methane	5		
Dissolved oxygen	5		
Residual chlorine	8		

[a] Significance in reporting data is represented by o.x, o.ox, and o.oox. The sensitivity provided is represented by:
o.x column with sensitivity down to 0.1 milligram per liter (mg/ℓ)
(0.1 mg/ℓ = 0.1 ppm = 100 μ/ℓ),
o.ox column with sensitivity down to 0.01 mg/ℓ
(10 μ/ℓ = 0.01 ppm) and
o.oox column with sensitivity down to 0.001 mg/ℓ
(1 μ/ℓ = 1 ppb).

investigations are not concerned with surface or bottom material, but rather with the body of the water. However, in groundwater pollution monitoring where percolated water is the prime interest, the bottom material may be of prime importance. The U.S. Environmental Protection Agency (1971) also presents data on organic pesticides sampling analysis. The cost of analysis of organic chemicals in groundwater is given in Table 15.

TABLE 15. COSTS OF ORGANIC CHEMICAL DETERMINATIONS FOR GROUNDWATER POLLUTION,[a] OCTOBER 1974

Parameter (mg/ℓ)	Water analysis cost ($)		
	o.x	o.ox	o.oox
Carbon in suspension	15		
Carbon dissolved	15		
Carbon total	15	25	
Biochemical oxygen demand	20		
Immediate oxygen demand	10		
Chemical oxygen demand	10		
Methylene blue active substances	10	15	
Nitrogen	10	11	
Phenolic material	15	17	20
Pesticides (insecticides and herbicides), each	40	42	45

[a] Significance in reporting data is represented by o.x, o.ox, and o.oox.

CONTAINERS. Organic substances tend to cling to sample containers and special precautions are necessary. Glass bottles are the most acceptable containers for collecting, transporting, and storing samples for organic analysis. Glass appears to be inert relative to organic materials and can withstand a rigorous cleaning procedure. Because organic materials are so plentiful in the environment, it is extremely difficult to collect samples free from extraneous contamination. Apparatus for containing samples must be scrupulously clean. Boston round-glass bottles of 1-liter capacity with sloping shoulders and narrow mouths are usually satisfactory. The closure should be inert metal, lined with teflon.

All sample bottles must be cleaned prior to sample collection. The accepted procedure is to wash the bottles in hot detergent solution, rinse them in warm tap water, then rinse them in dilute hydrochloric acid, and finally rinse them in distilled water. The bottles are then put into an oven at 300°C overnight. The teflon cap liners and metal closures are washed in detergent. The caps are rinsed with distilled water and air dried. The liners are rinsed in dilute hydrochloric acid, soaked in redistilled acetone for several hours, and heated at 200°C overnight. When the heat treatments are completed, the bottles are capped with the closure and teflon liners. The cost of glass bottles and mailers has been previously described.

SAMPLE PRESERVATION. Most water samples for organic analysis must be protected from degradation. Icing is the most acceptable method of preserving a sample. The U.S. Environmental Protection Agency (1974a) presents data for organic materials in water and wastes (Table 16). Goerlitz and Brown (1972) also recommend preservation techniques for organic substances in water. The procedures are similar, with the following additions:

Chlorophylls	Refrigerate at 4°C
Herbicides	Acidify with concentrated H_2SO_4 at a rate of 2 ml per liter of sample and refrigerate at 4°C.
Insecticides	None required for chlorinated compounds.

TABLE 16. RECOMMENDED SAMPLING AND PRESERVATION TECHNIQUES FOR ORGANIC CHEMICAL DETERMINATIONS

Measurement	Volume (ml)	Preservative	Holding time
Biological oxygen demand	1000	Cool to 4°C	6 hours
Chemical oxygen demand	50	H_2SO_4 to $pH < 2$	7 days
Methylene blue active substances (MBAS)	250	Cool to 4°C	24 hours
Nitrilotriacetic acid (NTA)	50	Cool to 4°C	24 hours
Oil and grease	1000	Cool to 4°C H_2SO_4 to $pH < 2$	24 hours
Organic carbon	25	Cool to 4°C H_2SO_4 to $pH < 2$	24 hours
Phenolics	500	Cool to 4°C H_2SO_4 to $pH < 4$ 1.0 g/l $CuSO_4$	24 hours
Kjeldahl nitrogen	500	Cool to 4°C H_2SO_4 to $pH < 2$	24 hours

Source: U.S. EPA (1974a)

Bacteriological

Coliform organisms have long been used as indicators of sewage pollution, although the group includes bacteria from diverse natural sources. For example, members of the coliform group may come from soil, water, and vegetation, as well as from feces. However, if a water sample contains an appreciable coliform count, the source of the sample is considered to have a disease-producing potential in the absence of contrary information. Standards for drinking-water quality provide criteria as to the number of coliform organisms allowable per 100 ml of finished water.

The standard test for presence of members of the coliform group may be carried out by the membrane filter technique or by the multiple-tube fermentation technique described by American Public Health Association (1971).

Fecal coliforms are that fraction of the coliform group that is present in the gut or the feces of warmblooded animals. They are capable of producing gas from lactose in a suitable culture medium at 44.5°C. Bacterial organisms from other sources generally cannot produce gas in this manner (American Public Health Association, 1971). The presence of fecal coliform organisms may indicate recent and possibly dangerous contamination. The presence of other coliform organisms suggests less recent contamination or contributions from sources of nonfecal origin.

Fecal streptococci are being used increasingly as indicators of significant contamination of water because the normal habitat of these organisms is the intestine of man and animals. Fecal streptococcal data verify fecal pollution and may provide additional information concerning the recency and probable origin of pollution. In combination with data on coliform bacteria, fecal streptococci are used in sanitary evaluation as a supplement to fecal coliforms where more precise determination of sources of contamination is necessary.

Samples for bacteriologic examination must be collected in bottles that have been carefully cleansed and autoclaved for 20 minutes at 212°C at 15 psi. Sterilized milk dilution bottles are ideal sample containers. When the sample is collected, ample air space must be left in the bottle to facilitate mixing of the sample by shaking. Care must be taken to avoid contamination of the sample and sample bottle at the time of collection and in the period prior to analysis.

As soon as possible after collection, preferably within 1 hour and not more than 6 hours, the sample should be filtered and the membrane filter placed on the growth medium. Samples must be kept cool during the time between collection and filtration. If filtration is delayed, the sample should be iced or refrigerated but not frozen.

The costs of bacterial analysis for groundwater pollution are given in Table 17.

TABLE 17. COSTS OF BACTERIAL ANALYSIS FOR GROUNDWATER POLLUTION, OCTOBER 1974

Bacteria	Cost ($)
Standard plate count	7
Coliform, fecal/100 $\mu\ell$	10
Coliform, total/100 $\mu\ell$	10
Enterococcus	10
Klebsiella – aerobacteria	10
Iron bacteria	9
Proteus	10
Pseudomonas aerceginosa	10
Staphylococcus	10
Salmonella	9
Sulfate reducing organisms	10
Streptococci, fecal	10
Streptococci, total	10
Bacteriological identification (90 percent complete)	35

Radiological

CONTAINERS. Radioactive elements are often measured in the submicrogram range and can therefore be influenced by any background or residual material that may be in the sample container. Similarly, a radionuclide may be largely or wholly adsorbed on the surface of suspended particles. Glass containers tend to have a higher background radioactivity than polyethylene bottles. For most radiochemical analyses (excluding tritium), a polyethylene bottle is recommended.

PRESERVATION. Radiochemical sample containers normally are washed with nitric acid and allowed to fume for several hours before use. After the sample has been taken and separated into suspended and dissolved fractions, a preservative can be added. The kind of preservative is highly dependent upon the kind of radiochemical to be analyzed. Formaldehyde or ethyl alcohol has been suggested as a preservative for highly perishable samples. Routinely in groundwater, however, hydrochloric and nitric acids are used as general preservatives. Preservatives and reagents should be tested for radioactivity prior to their use.

The costs of radiochemical analyses for groundwater pollution are given in Table 18.

TABLE 18. COSTS OF RADIOCHEMICAL ANALYSIS IN GROUND-WATER POLLUTION, OCTOBER 1974

Radiochemical	Cost ($)
Carbon-14 age date	160
Carbon 13/12 ratio	55
Cesium-137 diss.	22
Gamma-scan	70
Gross alpha and beta diss.	25
Gross alpha and beta susp.	25
Lead-210	25
Radium-226, by Radon	30
Strontium-90, diss.	35
Thorium-BTM colorimetric	25
Tritium, liq. scintillation	20
Uranium, diss.dir. fluorometric	18
Uranium, diss.extr. fluorometric	26

REFERENCES

Allison, L. E., "A Simple Device for Sampling Groundwaters in Auger Holes," Soil Science Society of America Proceedings, Vol 35, pp 844-845, 1971.

American Public Health Association, Standard Methods for the Examination of Water and Waste Water, American Public Health Association, New York, 874 pp, 1971.

American Society for Testing Materials, Manual on Water, ASTM Special Technical Publication, No. 442, 360 pp, 1969.

Anderson, J. T., E. E. Hardy, and J. T. Roach, A Land Use Classification System for Use with Remote-Sensor Data, U.S. Geological Survey Circular 671, U.S. Government Printing Office, Washington, D.C., 1972.

Anderson, K. E., Water Well Handbook, Missouri Water Well Drillers Association, 281 pp, 1967.

Apgar, M. A., and D. Langmuir, "Ground-Water Pollution Potential of a Landfill Above the Water Table," Ground Water, Vol 9, No. 6, pp 76-93, 1971.

Barnett, P. R., and E. C. Mallory, Jr., "Determination of Minor Elements in Water by Emission Spectroscopy," Chapter A2, Techniques of Water-Resources Investigations, Book 5, Laboratory Analysis, U.S. Geological Survey, 31 pp, 1971.

Barton, C. M., "Bore Hole Sampling of Saturated Uncemented Sands and Gravels," Ground Water, Vol 12, No. 3, pp 170-181, 1974.

Bentall, R., Methods of Collecting and Interpreting Groundwater Data, U.S. Geological Survey, Water-Supply Paper 1544-H, pp 36-46, 1963.

Black, C. A., (ed.), "Methods of Soil Analysis," (in two parts), Agronomy, No. 9, American Society of Agronomy, Madison, Wisconsin, 1969.

Blake, G. R., "Bulk Density," in "Methods of Soil Analyses, C. A. Black (ed.), Agronomy, No. 9, American Society of Agronomy, Madison, Wisconsin, pp 374-390, 1965.

Blaney, H. F., and W. D. Criddle, Determining Consumptive Use and Irrigation Water Requirements, U.S. Department of Agriculture Technical Bulletin 1275, 59 pp, 1962.

Bouwer, H., "Land Treatment of Liquid Waste: The Hydrologic System," Proceedings of the Joint Conference on Recycling Municipal Sludges and Effluents on Land, U.S. Environmental Protection Agency, U.S. Department of Agriculture, and the National Association of State Universities and Land-Grant Colleges, Champaign, Illinois, July 9-13, 1973.

Bower, C.A., and L.V. Wilcox, "Soluble Salts" in "Methods of Soil Analyses," C.A. Black (ed.) Agronomy, No. 9, pp 933-951, American Society of Agronomy, Madison, Wisconsin, 1965.

Bowman, I., Well-Drilling Methods, U.S. Geological Survey, Water Supply Paper 257, 139 pp, 1911.

Bredehoeft, J.D., and I.S. Papadopulos, "Rates of Vertical Ground Water Movement Estimated from Earth's Thermal Profile," Water Resources Research, Vol 1, No. 2, pp 325-328, 1965.

Brown, E., M.W. Skougstad, and M.J. Fishman, "Methods for Collection and Analysis of Water Samples for Dissolved Minerals and Gases," Chapter A1, Techniques of Water-Resources Investigations, Book 5, Laboratory Analysis, U.S. Geological Survey, 160 pp, 1970.

Brown, R.H., A.A. Konoplyantsev, J. Ineson, and V.S. Kovalevsky, "Ground-Water Studies," An International Guide for Research and Practice, UNESCO, Paris, 1972.

California Department of Water Resources, Water Well Standards, State of California, California Department of Water Resources, Bulletin 74, 1968.

California Office of Emergency Services, Emergency Plan, Sacramento, California, 310 pp, 1970.

Campbell, M.D., and J.H. Lehr, "Water Well Technology," Chapter 9, Formation Identification and Evaluation, McGraw-Hill Book Co., New York, 681 pp, 1973.

Cartwright, K., Temperature Prospecting for Shallow Glacial Aquifers in Illinois, Circular 433, Illinois State Geological Survey, 38 pp, 1968.

Cary, J.W., "Soil Water Flowmeters with Thermocouple Outputs," Soil Science Society of America Proceedings, Vol 37, pp 176-181, 1973.

Casagrande, A., "Seepage Through Dams," Journal of New England Water Works Association, June 1937.

Cederstrom, D.J., Cost Analysis of Ground-Water Supplies in the North Atlantic Region, U.S. Geological Survey Water Supply Paper 2034, 47 pp, 1970.

Chandler, P.B., W.L. Dowdy, and D.T. Hodder, Study to Evaluate the Utility of Aerial Surveillance Methods in Water Quality Monitoring, California State Water Resources Control Board, Publication No. 41, 100 pp, 1970.

Chapman, H.D., "Cation Exchange Capacity," in "Methods of Soil Analyses," C.A. Black (ed.), Agronomy, No. 9, pp 891-900, American Society of Agronomy, Madison, Wisconsin, 1965.

Childs, E.C., An Introduction to the Physical Basis of Soil Water Phenomena, Wiley-Interscience, 493 pp, 1969.

Cruff, R.W., and T.H. Thompson, A Comparison of Methods of Estimating Potential Evapotranspiration from Climatological Data in Arid and Subhumid Environments, U.S. Geological Survey Water Supply Paper 1839-M, 28 pp, 1967.

Davis, S.N., and R.J.M. DeWiest, Hydrogeology, John Wiley & Sons, Inc., New York, 463 pp, 1966.

Day, P.R., "Particle Fractionation and Particle Size Analyses," in "Methods of Soil Analyses," C.A. Black (ed.), Agronomy, No. 9, pp 545-566, American Society of Agronomy, Madison, Wisconsin, 1965.

Day, P.R., D.M. Anderson, and G.H. Bolt, "Nature of Soil Water," in "Irrigation of Agricultural Lands, R.M. Hazan, H.R. Haise, and T.W. Edminster (eds.), Agronomy, No. 9, pp 193-208, American Society of Agronomy, Madison, 1967.

Dunlap, W.J., and J.F. McNabb, Subsurface Biological Activity in Relation to Ground Water Pollution, Environmental Protection Technology Series, U.S. Environmental Protection Agency, Corvallis, Oregon, EPA-660/2-73-014, 1973.

Ellis, B.G., "The Soil as a Chemical Filter," Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland, W.E. Sopper and L.T. Kardos (eds.), the Pennsylvania State University Press, 1973.

Enfield, C.G., J.J.C. Hsieh, and A.W. Warrick, "Evaluation of Water Flux Above a Deep Water Table Using Thermocouple Psychrometers," Soil Science Society of America Proceedings, Vol 37, No. 6, pp 968-970, 1973.

Ferris, J.G., D.B. Knowles, R.H. Brown, and R.W. Stallman, Theory of Aquifer Tests, U.S. Geological Survey, Water Supply Paper 1536-E, pp 69-174, 1962.

Follansbee, R., "Evaporation from Reservoir Surfaces," American Society of Civil Engineers Transactions, Paper No. 1871, pp 704-715, 1933.

Forste, Robert H., Verification of Groundwater Capital Costs, Water Resources Research Center, University of New Hampshire, 1973.

Garber, M.S., and F.C. Koopman, "Methods of Measuring Water Levels in Deep Wells," Chapter A1, Techniques of Water-Resource Investigations, Book 8, U.S. Geological Survey, 23 pp, 1968.

Gardner, W.H., "Water Content," in "Methods of Soil Analyses," C.A. Black (ed.), Agronomy, No. 9, American Society of Agronomy, Madison, Wisconsin, pp 82-125, 1965.

Gibb, James P., Cost of Domestic Wells and Water Treatment in Illinois, Illinois State Water Survey Circular 104, 23 pp, 1971.

Gibson, U.P., and R.D. Singer, Water Well Manual, Premier Press, Berkeley, California, 156 pp, 1971.

Goerlitz, D.F., and E. Brown, "Methods for Analysis of Organic Substances in Water," Chapter A3, Techniques of Water-Resources Investigations, Book 5, Laboratory Analysis, U.S. Geological Survey, 40 pp, 1972.

Griffiths, D.H., and R.F. King, Applied Geophysics for Engineers and Geologists, Pergamon Press, 223 pp, 1969.

Guy, H.P., and V.W. Norman, "Field Methods for the Measurement of Fluvial Sediments," Chapter C2, Techniques of Water-Resources Investigations, Book 3, U.S. Geological Survey, 59 pp, 1970.

Hackbarth, D.A., "Field Study of Subsurface Spent Sulfite Liquor Movement Using Earth Resistivity Measurements," Ground Water, Vol 9, No. 3, pp 11-16, 1971.

Hansen, E.A., and A.R. Harris, "A Groundwater Profile Sampler," Water Resources Research, Vol 10, No. 2, 375 pp, 1974.

Hanshaw, B.B., W. Back, and M. Rubin, "Radiocarbon Determinations for Estimating Groundwater Flow Velocities in Central Florida," Science, Vol 148, pp 494-495, 1965.

Harbeck, G.E., Jr., M.A. Kohler, G.E. Koberg, et al., Water-Loss Investigations: Lake Mead Studies, U.S. Geological Survey, Professional Paper 298, 1958.

Havely, E., and A. Nir, "The Determination of Aquifer Parameters with the Aid of Radioactive Tracers," Journal of Geophysical Research, Vol 61, pp 2403-2409, 1962.

Hem, J.D., Study and Interpretation of the Chemical Characteristics of Natural Water, U.S. Geological Survey Water-Supply Paper 1473, second edition, 363 pp, 1970.

Holmes, J.W., S.A. Taylor, and S.J. Richards, "Measurement of Soil Water," in "Irrigation of Agricultural Lands," R.M. Hazan, H.R. Haise, and T.W. Edminster (eds.), Agronomy, No. 9, American Society of Agronomy, Madison, Wisconsin, pp 275-298, 1967.

Jacob, C.E., "Drawdown Test to Determine the Effective Radius of Artesian Wells," Transactions of the American Society of Civil Engineers, Vol 112, pp 1047-1070, 1947.

Johnson Division UOP, "Ground Water and Wells," A Reference Book for the Water-Well Industry, First Edition, Edward E. Johnson, Inc., St. Paul, Minnesota, 440 pp, 1966.

Johnson Division UOP, "Ground Water and Wells," A Reference Book for the Water-Well Industry, Second Edition, Edward E. Johnson, Inc., St. Paul, Minnesota, 440 pp, 1971.

Kaufman, W.J., and G.T. Orlob, "Measure of Groundwater Movement with Radioactive and Chemical Tracers," Journal of American Water Works Association, Vol 48, pp 559-572, 1956.

Keys, W.S., and L.M. MacCary, "Application of Borehole Geophysics to Water-Resources Investigations," Chapter E1, Techniques of Water-Resources Investigations, Book 2, U.S. Geological Survey, 126 pp, 1971.

Kirkham, D., and W.L. Powers, Advanced Soil Physics, Wiley Interscience, New York New York, 1972.

Klute, A., "Laboratory Measurement of Hydraulic Conductivity of Unsaturated Soil," in "Methods of Soil Analyses," C.A. Black (ed.), Agronomy, No. 9, pp 253-261, American Society of Agronomy, Madison, Wisconsin, 1965.

Kohler, M.A., Water-Loss Investigations: Lake Hefner Studies, Technical Report, U.S. Geological Survey, Professional Paper 269, 1954.

Lowry, R.L., and A.F. Johnson, "Consumptive Use of Water for Agriculture," American Society of Civil Engineers Transactions, Vol 107, pp 1243-1266, 1942.

Luthin, J.N. (ed.), Drainage of Agricultural Lands, American Society of Agronomy, Madison, Wisconson, 1957.

McMichael, F.C., and J.E. McKee, Wastewater Reclamation at Whittier Narrows, State of California, Water Quality Publication No. 33, 1966.

McNeil, B.L., "Soil Salts and their Effect on Water Movement," in "Drainage for Agriculture," J. van Schilfgaarde (ed.), Agronomy, No. 17, American Society of Agronomy, Madison, Wisconsin, pp 409-433, 1974.

Meinzer, O.E., "Ground Water," Hydrology, O.E. Meinzer (ed.), Dover Publications, Inc., New York, pp 385-477, 1942.

Merkel, R.H., "The Use of Resistivity Techniques to Delineate Acid Mine Drainage in Ground Water," Ground Water, Vol 10, No. 5, pp 38-42, 1972.

Merrill, S.D., and S.L. Rawlens, "Field Measurement of Soil Water Potential with Thermocouple Psychrometers," Soil Science, Vol 113, No. 2, pp 102-109, 1972.

Mortland, M.M., and W.D. Kemper, "Specific Surface," in "Methods of Soil Analyses," C.A. Black (ed.), Agronomy, No. 9, pp 532-543, American Society of Agronmy, Madison, Wisconsin, 1965.

Murrmann, R.P., and F.R. Koutz, "Role of Soil Chemical Processes in Reclamation of Wastewater Applied to Land," Wastewater Management by Disposal on the Land, U.S. Army Corps of Engineers, Cold Regions Research and Engineering Lab Specialty Report 171, 1972.

Myhre, D.L., J.O. Sanford, and W.F. Jones, "Apparatus and Techniques for Installing Access Tubes in Soil Profiles to Measure Soil Water," Soil Science, Vol 108, No. 4, pp 296-299, 1969.

Nielsen, D.R., J.W. Biggar, and K.T. Erh, "Spatial Variability of Field-Measured Soil-Water Properties," Hilgardia, Vol 42, No. 7, pp 215-260, 1973.

Osgood, J.O., "Hydrocarbon Dispersion in Ground Water: Significance and Characteristics," Ground Water, Vol 12, No. 6, November-December, 1974.

Oster, J.D., and L.S. Willardson, "Reliability of Salinity Sensors for the Management of Soil Salinity," Agronomy, Vol 63, pp 695-698, 1971.

Parizek, R.R., and B.E. Lane, "Soil-Water Sampling Using Pan and Deep Pressure-Vacuum Lysimeters," Journal of Hydrology, Vol 11, pp 1-21, 1970.

Penman, H.L., "Natural Evaporation from Open Water, Bare Soil, and Grass," Royal Society (London) Proceedings, Series A, Vol 193, pp 120-145, 1948.

Peters, D.B., "Water Availability," in "Methods of Soil Analyses," C.A. Black (ed.), Agronomy, No. 9, American Society of Agronomy, Madison, Wisconsin, pp 279-285, 1965.

Phene, C.J., G.J. Hoffman, and S.L. Rawlens, "Measuring Soil Matrix Potential in-situ by Sensing Heat Dissipation Within a Porous Body: I, Theory and Sensor Construction," and "II, Experimental Results," Soil Science Society of America Proceedings, Vol 35, pp 225-229, 1971.

Poulton, C.E., "A Comprehensive Remote Sensing Legend System for the Ecological Characterization and Annotation of Natural and Altered Landscapes," Proceedings of the Eighth International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, 1972.

Pratt, P. R., *Nitrate in the Unsaturated Zone Under Agricultural Lands*, U.S. Environmental Protection Agency, Water Pollution Control Research Series, 16060 DOE 04/72, 45 pp, 1972.

Rainwater, F.H., and L.L. Thatcher, *Methods for Collection and Analysis of Water Samples*, U.S. Geological Survey Water-Supply Paper 1454, 301 pp, 1960.

Ralston, D.R., *Influences of Water Well Design on Neutron Logging*, unpublished M.S. Thesis, University of Arizona, Tucson, Arizona, 1967.

Rawlens, S.L., and F.N. Dalton, "Psychrometric Measurement of Soil Water Potential Without Precise Temperature Control," *Soil Science Society of America Proceedings*, Vol 31, pp 201-297, 1967.

Ray, R.G., *Aerial Photographs in Geologic Interpretation and Mapping*, U.S. Geological Survey, Professional Paper 373, pp 201-297, 1960.

Reeve, R.C., "Hydraulic Head," in "Methods of Soil Analyses," C.A. Black (ed.), *Agronomy*, No. 9, pp 180-196, American Society of Agronomy, Madison, Wisconsin, 1965.

Reitemeier, R.F., "Effect of Moisture Content on the Dissolved and Exchangeable Ions of Soils of Arid Regions," *Soil Science*, Vol 61, No. 3, pp 195-214, 1946.

Rhoades, J.D., and L. Bernstein, "Chemical, Physical and Biological Characteristics of Irrigation and Soil Water," *Water and Water Pollution Handbook*, Vol 1, L.L. Ciaccio (ed.), Marcel Dekker, Inc., New York, pp 142-222, 1971.

Richards, L.A. (ed.), *Diagnosis and Improvement of Saline and Alkali Soils*, U.S. Department of Agriculture, Agricultural Handbook 60, 1954.

Richards, L.A., "A Soil Salinity Sensor of Improved Design," *Soil Science Society of America Proceedings*, Vol 30, 11 333-337, 1966.

Rohwer, C., "Evaporation from Different Types of Pans," *American Society of Civil Engineers Transactions*, Paper No. 1871, 1933.

Sammel, E.A., "Convective Flow and its Effect on Temperature Logging in Small-Diameter Wells," *Geophysics*, Vol 33, No. 6, pp 1004-1012, 1968.

Seker, J., "Hydrologic Significance of Tectonic Fractures Detectable on Airphotos," *Ground Water*, Vol 4, No. 4, pp 23-27, 1966.

Simonson, R.W., "What Soils Are," in "Soil," *The Yearbook of Agriculture*, U.S. Department of Agriculture, Washington, D.C., pp 17-30, 1957.

Skibitzke, H.E., *Electronic Computers as an Aid to the Analysis of Hydrogeological Problems*, International Association of Scientific Hydrology, Publication 52, Brussels, pp 347-358, 1960.

Smith, D.B., "Flow Tracing Using Isotopes," *Groundwater Pollution in Europe*, J.A. Cole (ed.), Water Information Center, Port Washington, New York, pp 377-387, 1974.

Stallman, R.W., *Electric Analog of Three-Dimensional Flow to Wells and Its Application to Unconfined Aquifers*, U.S. Geological Survey, Water-Supply Paper, 1536-4, pp 205-242, 1963.

Stollar, R.L., and P. Roux, "Earth Resistivity Surveys—A Method for Defining Ground-Water Contamination," *Ground Water*, Vol 13, No. 2, pp 145-150, 1975.

Stout, P.R., R.G. Burau, and W.A. Allardice, *A Study of the Vertical Movement of Nitrogenous Matter from the Ground Surface to the Water Table in the Vicinity of Grover City and Arroyo Grande—San Luis Obispo County*, Report to Central Coastal Regional Water Pollution Control Board, 51 pp, 1965.

Theis, C.V., "The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground-Water Storage," *Transactions of the American Geophysical Union*, Part 2, pp 519-524, 1935.

Thomas, G.W., and B.J. Barfield, "The Unreliability of Tile Effluent for Monitoring Subsurface Nitrate-Nitrogen Losses from Soils," *Journal of Environmental Quality*, Vol 3, No. 2, pp 183-185, 1974.

Thorley, G.A., *Regional Agricultural Surveys Using ERTS-1 Data*, Center for Remote Sensing Research, ERTS-1 Final Report, Berkeley, California, 1973.

Thornthwaite, C.W., "An Approach Toward a Rational Classification of Climate," *Geographic Reviews*, Vol 38, pp 55-94, 1948.

Todd, D.K., *Ground Water Hydrology*, John Wiley & Sons, New York, 336 pp, 1959.

Todd, D.K., R.M. Tinlin, K.D. Schmidt, and L.G. Everett, *Monitoring Groundwater Quality: Monitoring Methodology*, (in press), U.S. Environmental Protection Agency, Las Vegas, Nevada, 1976.

Turcan, A.N., *Calculation of Water Quality from Electrical Logs—Theory and Practice*, Louisiana Geological Survey, Water Resources Pamphlet 19, 23 pp, 1966.

UNESCO, "Measurement of Groundwater Flow Velocity," Part 7.4.2, *Ground-Water Studies, An International Guide for Research and Products*, 1975.

U.S. Departments of the Army and Air Force, *Wells*, Technical Manual TM5-197, Washington, D.C., 264 pp, 1957.

U.S. Environmental Protection Agency, Methods for Organic Pesticides in Water and Wastewater, National Environmental Research Center, Cincinnati, Ohio, U.S. Government Printing Office, 759-301/2113, 47 pp, 1971.

U.S. Environmental Protection Agency, Handbook for Analytical Quality Control in Water and Wastewater Laboratories, Analytical Qaulity Control Laboratory, National Environmental Research Center, Cincinnati, Ohio, U.S. Government Printing Office, 479-971, 54 pp, 1972.

U.S. Environmental Protection Agency, Handbook for Monitoring Industrial Wastewater, Technology Transfer Series, U.S. Government Printing Office, 732-349/414, 91 pp, 1973.

U.S. Environmental Protection Agency, Manual of Methods for Chemical Analysis of Water and Wastes, EPA-625-15-75-003, Methods Development and Quality Assurance Research Laboratory, National Environmental Research Center, Cincinnati, Ohio, 298 pp, 1974a.

U.S. Environmental Protection Agency, "Water Quality and Pollutant Source Monitoring," Federal Register, Vol 39, No. 168, Part III, 1974b.

U.S. Environmental Protection Agency, "Model State Water Monitoring Program," EPA-440/9-74-002, Office of Water and Hazardous Materials Monitoring and Data Support Division, Washington, D.C. 36 pp, 1975.

U.S. Geological Survey, Techniques of Water Resources Investigations, Book 5, Laboratory Analysis, 1973.

Van Bavel, C.H.M., "Neutron Scattering Measurement of Soil Moisture: Development and Current Status," Proceedings of International Symposium on Humidity and Moisture, Washington, D.C., pp 171-184, 1963.

van Schilfgaarde, J., "Drainage for Agriculture," Agronomy, No. 17, American Society of Agronomy, Madison, Wisconsin, pp 359-405, 1974.

Walton, W.C., Groundwater Resource Evaluation, McGraw-Hill Book Co., New York, 664 pp, 1970.

Walton, W.C., and T.A. Prickett, "Hydrogeologic Electric Analog Computer," Proceedings of the American Society of Civil Engineers, Journal of the Hydraulics Division, Vol 89, pp 67-91, 1963.

Watson, K.K., "A Recording Field Tensiometer with Rapid Response Characteristics," Journal of Hydrology, Vol 5, pp 33-39, 1967.

Watson, K.K., "Some Applications of Unsaturated Flow Theory," in "Drainage for Agriculture," J. van Schilfgaarde (ed.), Agronomy, No. 17, American Society of Agronomy, Madison, Wisconsin, 1974.

Willardson, L.S., B.D. Meek, and M.J. Huber, "A Flow Path Ground Water Sampler," Soil Science Society of America Proceedings, Vol 36, pp 965-966, 1973.

Wilson, L.G., Observations on Water Content Changes in Stratified Sediments During Pit Recharge," Ground Water, Vol 9, No. 3, pp 29-40, 1971.

Wilson, L.G., and K.J. DeCook, "Field Observations on Changes in the Subsurface Water Regime During Influent Seepage in the Santa Cruz River," Water Resources Research, Vol 4, No. 6, pp 1219-1234, 1968.

Wood, W.W., "A Technique Using Porous Cups for Water Sampling at any Depth in the Unsaturated Zone," Water Resources Research, Vol 9, No. 2, pp 486-488, 1973.

Yare, B.S., "The Use of a Specialized Drilling and Groundwater Sampling Technique for Delineation of Hexavalent Chromium Contamination in an Unconfined Aquifer, Southern New Jersey Plain," Ground Water, Vol 13, No. 2, pp 151-154, 1975.

Zohdy, A.A., G.P. Eaton, and D.R. Mabey, "Application of Surface Geophysics to Ground-Water Investigations," Chapter D1, Techniques of Water-Resources Investigations, Book 2, Collection of Environmental Data, U.S. Geological Survey, 116 pp, 1974.

APPENDIX

METRIC CONVERSION TABLE*

Non-Metric Unit	Multiply by	Metric Unit
inch (in)	25.4	millimeters (mm)
feet (ft)	0.3048	meters (m)
miles	1.60934	kilometers (km)
acres	0.404686	hectares (ha)
grains	64.79891	milligrams (mg)
gallons (gal)	3.7854	liters (l)
pounds per square inch (psi)	0.0680460	atmospheres (atm)
parts per million (ppm)	1	milligrams per liter (mg/l)
gallons per minute (gpm)	3.7854	liters (l) per minute
gallons per hour (gph)	3.7854	liters (l) per hour

---

*English units were used in this report because the data obtained were not available in metric units.